Department of Informatics

V2VUNet: An Approach to a Three-dimensional Forwarding Scheme in Inter-vehicle Communications

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The Faculty of Business, Economics and Informatics of the University of Zurich hereby authorizes the printing of this dissertation, without indicating an opinion of the views expressed in the work.

Zurich, October 25, 2017

Chairman of the Doctoral Board: Prof. Dr. Sven Seuken

For my mother Milka Handayani and my brother Daniel Angga Wibisana Halim in Heaven.

Abstract

The demand for mobile communications has been increasing over the last decades. This demand is indicated by various information interchanges during a human's trip on a daily basis. In order to facilitate this demand, the Inter-vehicular Communication (IVC) is one of promising solutions that supports massive information interchanges. The inter-vehicular communication has been investigated and evaluated under several conditions such as in a 3-dimensional environment. The 3-dimensional environment becomes a challenge on the network layer field: the problem in forwarding a data packet. The packet forwarding should show a resilient behavior since it plays the important role to transmit data packets through several issues: the inevitable obstruction, loss connections, and a short duration of connectivity. Therefore, the challenges of modeling and improving such packet forwarding ones are use case specific. This thesis focuses on the network layer since the packet forwarding scheme determines the software that can be modified and engineered in order to optimize this method in particular and very practical use cases.

The newly proposed Vehicular-to-vehicular Urban Network (V2VUNet) developed two refined approaches, which extend and improve the traditional forwarding schemes with respect to a more complex 3-dimensional environment. The first approach has the property of limiting the number of intermediate candidates of vehicles by restricting the area of searching. The second approach is the predicting forwarding scheme as the improvement of the area restriction forwarding scheme.

Both approaches introduce the Vertical Relative Angle (VRA) as the new parameter in measuring location coordinates of vehicles, particularly in a 3-dimensional area. If, however, VRA is often calculated, it becomes a less significant parameter in most forwarding methods due to its oversimplification in 3-dimensional environments. As a result, the forwarding algorithm's

impracticality was overcome by adding a component for the consideration of various road topology levels. This leads to a detailed investigation of such use case under consideration.

This thesis evaluates V2VUNet in many scenarios from a simple 3-dimensional environment to a complex one, and various parameters in order to determine and investigate on a suitable solution for such use cases. On one hand, the V2VUNet: the area restriction forwarding scheme shows as a result by now a solution to a 3-dimensional environment. On the other hand, V2VUNet: the prediction forwarding scheme reduces the delay significantly. Finally, the enhanced V2VUNet as the combination of the area restriction and prediction forwarding scheme shows the better performance compared to the traditional forwarding scheme.

Kurzfassung

Bis heute ist die Nachfrage für eine Unterstützung mobiler Kommunikation in jeder Lebenslage stetig gestiegen und wird auch zukünftig noch weiter zunehmen. Diese Entwicklung wird sowohl durch Technologieentwicklungen induziert als auch durch den persönlichen Bedarf nach dauerhafter Erreichbarkeit und einem Datenaustausch, speziell während Reisen oder Fahrten zum Arbeitsplatz. Ein vielversprechender Ansatzpunkt, um diesen Bedarf explizit zu adressieren, ist die Einbindung der Fahrzeuge selber in die Kommunikationsinfrastruktur. Diese Idee wird seit geraumer Zeit in der Forschung verfolgt und evaluiert. Bedingt durch bauliche Begebenheiten (bspw. Brücken, Tunnel oder enge Bebauungen) in Ballungsräumen ergeben sich diverse Probleme bei der Weiterleitung von Datenpaketen auf der Netzwerkschicht, da nun dreidimensionalle Lösungsansätze benötigt werden. Diese Begebenheiten beeinflussen im besonderen sehr stark die Netzwerkstabilität, da es zu eingeschränkter Konnektivität kommen kann, teilweise sogar zu unvorhersehbaren Verbindungsabbrüchen. Daher ist die Modellierung der Datenpaketweiterleitung und deren Verbesserung stark umgebungsabhängig und anwendungsspezifisch.

Die in der vorliegenden Arbeit entwickelte Lösung, Vehicular-to-vehicular Urban Network (V2VUNet) genannt, verfolgt eine Kombination aus zwei Ansätzen, um traditionelle Weiterleitungsverfahren hinsichtlich der dreidimensionalen Umgebung zu optimieren. Ziel des ersten Ansatzes ist es, die Anzahl der Zwischenkandidaten in der Kommunikation in einem Suchbereich zu minimieren. Dieser wird vom zweiten Ansatz mit einem Fokus auf die Vorhersagen, wie Datenpakete weitergeleitet werden sollen, ergänzt.

Beide Ansätze verwenden den sogenannten “Vertical Relative Angle (VRA)” als zusätzlichen Parameter, um die Positionskoordination im drei-

dimensionalen Bereich zu messen. Je öfter dieser Parameter berechnet wird, desto weniger bedeutend wird dieser für die meisten Weiterleitungsverfahren, welches durch die Vergröberung im dreidimensionalen Bereich bedingt ist. Um dieses Defizit auszugleichen, muß eine weitere Komponente – die Straßentopologie – in die Berechnungen mit einbezogen werden.

Die vorliegende Arbeit evaluiert V2VUNet in verschiedenen Umgebungen, ausgehend von einer einfachen dreidimensionalen Umgebung bis hin zu einer komplexen Umgebung unter Beachtung diverser Parameter (beispielsweise der Fahrzeuggeschwindigkeit, von Distanzen, Höhen und der Fahrzeuganzahl in der Umgebung). Es hat sich gezeigt, daß das Weiterleitungsschema von V2VUNet die Anzahl der möglichen Weiterleitungskandidaten stark minimiert und die Vorhersage des Weiterleitungsschemas die Verzögerung in der Weiterleitung signifikant reduziert. Die Kombination dieser beiden Methoden zeigt in den vorliegenden und untersuchten Szenarien im Vergleich zu den klassischen Weiterleitungsmethoden, welche typischerweise heutzutage verwendet werden, eine deutlich bessere Leistungsfähigkeit.

Contents

1 Introduction

Over the last decade, the increasing demand for mobile communications is shown by various types of mobile applications along with a growing number of information traffic exchanges. The mobile communication is deemed essential by most end-users during their commute with public transportations or with their private cars. Considering the mobile communication with a public transportation, a vehicular communication provides a promising platform to cope the mobile communication requirement. Vehicular communications implement among other the concept of Vehicular Ad-hoc Network (VANET), which consider moving vehicles as network nodes as shown in Figure 1.1.

The concept of VANET is categorized into three different concepts, based on the elements of the network [72]. The first concept is known as Vehicle-to-Infrastructure (V2I), integrating vehicles and infrastructures support such as Road Side Unit (RSU). The second concept provides the interaction between vehicles without any support of infrastructure, which is also known as Vehicle-to-Vehicle (V2V) or Inter-Vehicular Communication (IVC) [79]. The third concept combines both advantages of V2V and V2I as a hybrid VANET communication addressing the general challenges in developing VANET communications.

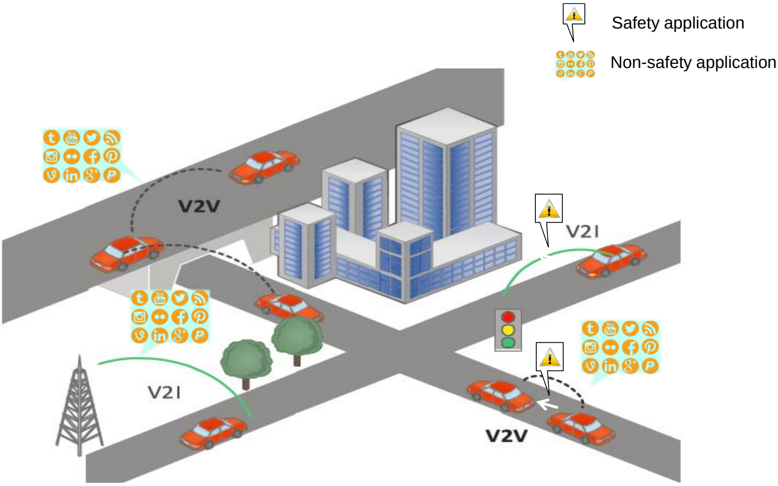


Figure 1.1: VANETs Communication

There are two advantages of implementing the VANET. The first advantage is that the VANET is able to be a promising solution due to the absence of a fixed infrastructure. For instance, in a case of 3-dimensional topologies, especially such as underpasses and overpasses, a mobile communication shows a poor performance because of the overpass construction partly blocks the connectivity between a mobile device and the Global Positioning System (GPS) [41]. The GPS as the location coordinates provider, shows inaccuracy in providing position coordinates of respective vehicles. The other cases regarding the availability of infrastructures are influenced by factors such as a cost of installations, a road topology complexity, and lack of cooperation between private sector and government also motivates the implementation of VANET. These cases will be addressed by assuming the existence of vehicles as the moving infrastructure [71]. The second advantage is the direct communication among vehicles and Road Side Units (RSUs) within their transmission distance. It provides various safety applications, *e.g.,* information and alert functions, a cooperative system, and a longitudinal coordinate information [59].

As a part of VANET communication, one such communication that has received a lot of interest is the IVC. The main advantage of implementing IVC is its ability to reserve network resources, which leads to a resource efficiency and a delay constraint aspects. The resource efficiency addresses the reduction of infrastructure utilization, for instance, a warning signal can be directly transmitted between two vehicles instead of involving a cellular base station as the communication interface. Thus, by reducing the infrastructure utilization, the delay can be compressed.

1.1 Inter-vehicular Communication

Inter-vehicular Communication (IVC) offers several potential applications, which can be classified – based on purposes – into driving-related, passenger-related, and vehicle-related applications [53]. Driving-related applications support a driver to obtain the traffic efficiency and safety by aggregating the road-related information *e.g.,* vehicle direction, speed, road surface, and traffic jam. Passenger-related applications emphasize on convenience and comfort of the passenger, whereas vehicle-related applications do not have impact on drivers and passengers, except to improve the operation of vehicles. Passenger-related applications *e.g.,* infotainment, social media access, and Web surfing, are even possible to be implemented in IVC. However, external RSU is necessary to provide the Internet access.

There are two promising alternatives to perform IVC. The cellular-based network is the first alternative that exists with competitive cost nowadays. The utilization of cellular network is widely applied because of its scalability adopting the concept of smaller cells to increase the coverage. However, faster, cheaper, and more efficient data exchanges in some cases are obtained by implementing the direct communication style: non-cellular network [30].

The second alternative, an ad-hoc-based network becomes more appropriate in developing IVC. Major considerations in deploying IVC include:

- Economical consideration: in the future, vehicles are equipped with the wireless technology standard, *i.e.,* Wireless Access in the Vehicular Environment (WAVE), thus, it can reduce the cellular cost

- Social consideration: since many people use their mobile phone during their commute, thus, it leads to large masses of data ready for communications

- Resource and technology consideration: in future deployment when all vehicles are able to communicate with each other, IVC will support a mobile application that does not require a cellular network

1.2 Large City Environment

In 2015, there were 13 millions vehicles which are registered in Jakarta, Indonesia [62]. It causes the road traffic more denser in rush hours. As a consequence, non-uniform mobility and density lead to a short connection life time as illustrated in Figure 1.2. High-rise buildings and diverse road topologies such as roads with intersections and overpasses, are the common objects that exist in a large city environment. Jakarta represents as an example a large city in a developing country, which has complex road topologies. This typical condition reflects the particular large city environment, and such an environment is modeled within this thesis as illustrated in Figures 1.3 and 1.4. The details of this large city environment are described further in Chapter 2.

In addition to the large environment, the 3-dimensional topology of a road becomes an issue to the Global Positioning System (GPS)'s signal reception. The GPS receiver uses the speed and direction of a vehicle to determine the vehicle's position. Figure 1.5 shows the connection lost of GPS which occurs under an overpass. This missing location coordinate indicates that connectivity is influenced by the inevitable obstacle, in this case the overpass construction. Another solution of missing location coordinate can be mitigated by dedicated forwarder. However, in particular condition such as in sparse network, a mitigated forwarder can be a problem due to its

Figure 1.2: Non-uniform Traffic in Jakarta, Indonesia

infrequent availability. The arrows in the Figure 1.5 indicate the two occurring signal loss periods while driving beneath two overpasses. This missing connectivity issue requires a particular attention in order to support a successful packet transmission.

The 3-dimensional road topology and its impact to the IVC's performance is the main concern of this thesis. This 3-dimensional road topology has been discovered in several other papers [46], [31]. Those papers focus on the complexity of implementing a packet forwarding scheme in the 3-dimensional road topology. However, there are missing factors such as the proper propagation model, in their packet forwarding process. During the packet forwarding process, three communication layers: physical layer, MAC layer, and network layer, are the important architecture of protocols in transmission and reception phases. These protocols and their association with the packet transmission process are described in Chapter 2.

Figure 1.3: Large City Environment in Indonesia

1.3 Thesis Contribution

Motivated by the above observations, this thesis contributes to forwarding schemes in IVC. These forwarding schemes are improved by looking at the distance, direction, and relative angle parameters. These parameters are calculated from a sender to receiver vehicle, and simulated in a specific scenario, to determine the network performance. The network performance is measured mainly by evaluating the Packet Delivery Ratio (PDR) and delays.

The complex road topology, vehicle's mobility, and traffic density in Jakarta city are modeled using a web mapping service. By simulating those conditions, this thesis provides and evaluates the real situation of Jakarta as a use case. The overall contributions in this thesis are the following:

- It provides a specific model of a large city environment. This model can be used as a preliminary requirement for further studies such as in traffic and transportation problems.

- It can increase the level of representation from a simple 3-dimensional to a complex 3-dimensional road topologies, from one

Figure 1.4: A Complex Road Topology

height to different heights road topologies. Thus, it can be useful for an actual implementation.

- It proposes a packet forwarding scheme and adds a new parameter in designing the relevant packet forwarding algorithm.

This thesis contribution is for the Indonesian Government, funded by Indonesian Ministry of Education, to provide input for networking infrastructure planning purposes.

The 3-dimensional environment and their inevitable obstructions are addressed. Thus, the packet forwarding scheme is designed to accommodate a possible connection when the communication between two vehicles occurs in any road topology levels. This condition is modeled to increase the complexity of the 3-dimensional environment.

This thesis introduces the relative-angle parameter as an approach to model the 3-dimensional environment. This relative-angle parameter is determined as two types depending on the road topology level. The first type of relative-angle is implemented on a 2-dimensional area and the second one is implemented on a 3-dimensional area. These two types of relative

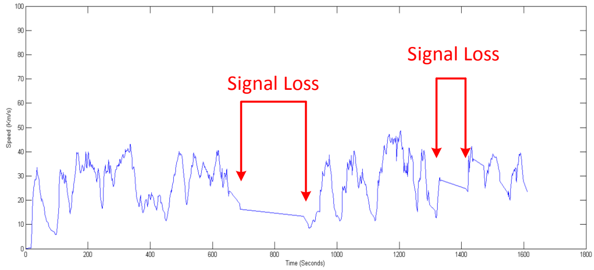


Figure 1.5: GPS Connection Lost Occurs Under the Overpass

angles integrate the particular propagation model and the vehicle mobility model in a large city scenario. The propagation model focuses on diffraction propagation since the overpass is formed as a massive and opaque object. Therefore, the transmission through such of concrete material is not possible. The mobility model includes the duration of moving vehicles entering and departing the underpass.

1.4 Thesis Outline

Chapter 2 highlights the goal, challenges, and the 3-dimensional use case of the IVC. The external factors: environments, connectivity models, and traffics, that influence the IVC, are described in details. These factors explicate the challenges in modeling and improving the reliable IVC. The related topic: a radio propagation, is presented to illustrate the signal behavior due to the external factors. Finally, the research focus and contribution of this thesis are introduced.

Chapter 3 explores the internal components: the IVC technology and the forwarding strategy. The IVC technology: Wireless Access in Vehicular Environments (WAVE) and the channel modeling are discussed in detail. Finally, the Horizontal Relative Angle (HRA) and the Vertical Relative Angle (VRA) are introduced as the additional weight values to the forwarding strategy.

Chapter 4 improves and design two approaches in the packet forwarding scheme. These two approaches: the area restriction forwarding scheme and the path prediction forwarding scheme, apply the HRA and VRA. Finally, the area restriction and the path prediction forwarding scheme are combined to take the benefit of each forwarding scheme.

Chapter 5 shows the initial results of a traditional forwarding scheme. These results are required as the comparison of existing forwarding schemes. The complete description and requirement environment are also provided as well as communication models. All models are simulated in Network Simulation-3 (NS3) environment.

Chapter 6 shows the final results and evaluates the area restriction and the path prediction forwarding scheme in given road traffics, simple and complex road topologies, and communication models.

Chapter 7 concludes the thesis. It reviews the two approaches proposed and their findings, and ends with a view on possible future work.

2
Reliable Inter-vehicular Communication

The inter-vehicular communication refers to a communication among vehicles. This communication specifies the direct connectivity among vehicles and interchanges information. Several projects have been deploying IVC such as in the Car-to-Car Communication (C2CC) [18], CarTALK 2000 [59], NoW – Network on Wheels [1], and FleetNet [21] are the IVC projects which are designed to improve the safety of all traffic participants. Those IVC related projects show the possibility of direct communication amongst vehicles.

In general, all those projects emphasize a reliable communication due to IVC's challenges *i.e.*, the high mobility of participating vehicles and the infrastructure-less properties. Therefore, the main goal is to ensure the direct and cooperative communication among vehicles available in real time and continuously. In addition, the reliable connectivity guarantees a successful packet transmission, although a broken path occurs due to frequent topology changes [20], [64] or other potential factors such as a traffic and an environment. The packet is stated as "successfully delivered" when the packet reaches a destination point. Thus, the reliable communication shows a Packet Delivery Ratio (PDR) which is nearly to 100% in an overall transmission processes. In addition to that, a delay as a consequence of the transmission process is reduced to be as low as possible at any reasonable packet sizes and data rates.

In order to establish a reliable IVC, several external factors need to be considered. These external factors are classified as the environment, traffic, and connectivity model as shown in Figure 2.1. Those factors are explained in detail in the following subsections.

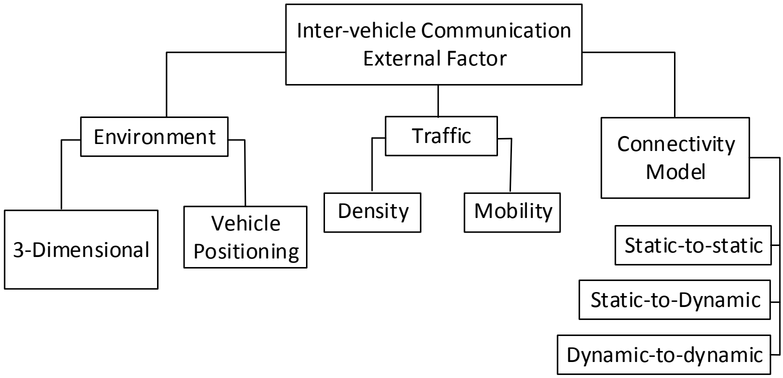


Figure 2.1: Inter-vehicle Communication External Factors

2.1 Environment

In general, a large city has numerous objects such as buildings, overpasses, intersections, and ramps. Taking into account these existing objects, the large city environment can be derived into two topics: the 3-dimensional environment and the vehicle positioning. On one hand, the 3-dimensional environment is raised due to the existence of buildings and overpass. On the other hand, the vehicle positioning describes the location coordinate of vehicles as the impact of the 3-dimensional environment. Those topics are described in detail in Subsections 2.1.1 and 2.1.2.

2.1.1 Three-dimensional Environment

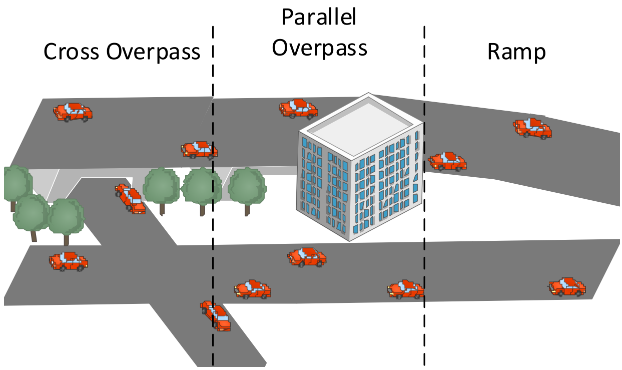


Figure 2.2: Three-dimensional Cases

There are several fields that can benefit from the implementation of the 3-dimensional environment, such as the field of Wireless Sensor Network (WSN), the field of the Unmanned Aerial Vehicle (UAV), and the field of Autonomous Underwater Vehicle (AUV) communication network. In the WSN field, the communicating nodes are mostly at a quasi-static (slow changing) movement [55]. While in the fields of UAV and AUV networks, the communicating nodes are moving with unconstrained trajectories . In IVC network, vehicles are also moving in a 3-dimensional environment in a particular case, more similar to the aerial and underwater vehicles but with constrained trajectories, following the road trajectories. Each field introduces different challenges. For example, in UAV, a weather condition may strongly affect its connectivity [6]. In AUV, water absorbs almost electromagnetic waves, making an underwater communication does not scale for more than 10 m [32]. While in IVC, building and overpass are the main components that affect the propagation. Table 2.1 shows a comparison of 3-dimensional networks as explained previously. The significant difference of WSN, UAV, AUV, and IVC points out inevitable objects such as overpasses, buildings, and other vehicles that distract the transmission.

Table 2.1: Comparison of 3-dimensional Networks

Issue	3D Network			
	WSN	UAV	AUV	IVC
Connectivity limitation	Energy constraint	Water absorption	Bad weather	Inevitable object
Mobility	Static /Quasi-static	Unconstrained trajectory	Unconstrained trajectory	Constrained trajectory
Propagation medium	Air	Water	Air	Air

2.1.2 Vehicle Positioning

In IVC, calculating a vehicle's position is necessary to achieve the efficient transmission between a sender and a receiver. The vehicle's position is assumed being provided by the Global Positioning System (GPS) [34]. The location coordinate acquisition is guaranteed by GPS which provides three coordinate axis *i.,.e., x, y, z* represent longitude, latitude, and elevation respectively [74]. Those location coordinates obtain the vehicle's position and other participating vehicles in real time. GPS uses at least three satellites to calculate the 2-dimensional position (latitude and longitude) and to track the movement. With four or more satellites, the 3-dimensional location coordinates (latitude, longitude, and elevation) can be determined. In case of the 3-dimensional environment, location coordinates in the 2-dimensional environment are applied and ignores the third location coordinate: the z-axis. Thus, in a condition where the elevation of an object has a non-zero value, it becomes significant to consider the z-axis coordinate. Figure 2.2 shows vehicles which are located on the lower and the upper road topology. Thus, to obtain the vehicle's position accuracy, the elevation or geometric height is considered as an additional location coordinate. The vehicle's location coordinate in real life will impact the packet transmission due to particular radio propagation [61], which is described in Section 2.4.

2.2 Traffic

The second external factor is the traffic, which is divided into traffic density and traffic mobility. The traffic density refers to a number of vehicles, which are participating in the particular time and location. The traffic mobility refers to the communicating vehicles, which move in various directions: the opposite or the same direction, in pre-defined roads. The traffic density and mobility are presented in the next subsections.

2.2.1 Traffic Density

The traffic density identifies the number of participating vehicles. These participating vehicles are assumed to be those vehicles which are actively involved in the communication process such as transmitting, receiving, and relaying packets. Based on the number of active participating vehicles, the network density is classified into two classes: the dense and sparse network.

A dense network involves many participating vehicles. There exists no definition of a network being called dense or sparse. However, there is a formula that can be used to identify the density of a network as shown in Eg.2.1.

$$q = uk \tag{2.1}$$

This formula is based on the calculation of traffic flow density [12]. Traffic-flow theories explore relationships among the main quantities: the vehicle density, the flow, and the speed. The flow q measures the number of vehicles that pass an observer per unit time. The density k represents the number of vehicles per unit distance. The speed u is the distance that a vehicle travels per unit time.

The dense network has an advantage regarding a connection availability. Under the assumption that all participating vehicles are equipped with the location information equipment, the connection availability is assumed to be reliable. However, in a case where the traffic is too dense (crowded), the strategy in order to reduce the number of those participants should be considered. In addition, the dense network usually occurs in a busy hour. Therefore, the vehicle mobility is assumed to be slow.

On the contrary of a dense network, a sparse network is the network that has infrequent connectivity. The sparse network can be the network with numerous vehicles with a less vehicle connectivity, or the network with a few vehicles. As a consequence, a sparse network requires such optimization and a specific strategy in a forwarding scheme, which is explained in Section 3.2.

2.2.2 Traffic Mobility

There are two components in the traffic mobility: the speed and direction. These two components influence the mobility pattern where participating vehicles can run at high or low speed, and in heterogeneous or homogeneous directions.

Generally, vehicles can move at high speed, *i.e.,* up to 220 km/h, on a highway with the absence of any accidents or distractions. On the contrary, vehicles can only move at low speed, *i.e.,* maximum 50 km/h, on a road where the traffic jam occurs in a rush hour. These various speeds lead to several researches that have conducted work to show the impact of high-/low speed vehicles on a network performance [44].

In IVC, most of the vehicles move in a constrained trajectory since the vehicles have to follow the pre-defined road path. As previously mentioned, the heterogeneous and homogeneous directions of vehicles [65] also affect the network performance [10].

IVC with a high speed and heterogeneous direction show a high possibility to result in frequent topology changes. These frequent topology changes initiate an appropriate strategy to obtain location information in real time. For instance, applying the predicting strategy in a network design [52].

2.3 Connectivity Model

Due to the basic property of IVC, the last external factor is defined as the connectivity model. The connectivity is classified based on traffic conditions: Static-to-static (S2S), Static-to-dynamic (S2D), and Dynamic-to-dynamic (D2D). The S2S condition occurs during the traffic congestion, where at particular time all participating vehicles are not moving. The S2D condition describes a combination of moderate traffic and traffic congestion, and the D2D condition describes a road during moderate traffic where it is assumed that all vehicles are moving in high speeds. These three conditions lead to a deeper investigation in a duration of connection among vehicles. On one hand, the S2S condition seems to show a longer duration of connection because the packet transmission process continues when communicating vehicles can maintain their current position. On the other hand, the D2D condition seems to have a frequent disconnection because of the communicating vehicle's mobility. Those models reflect the real behavior of vehicular communication in a large city traffic.

Having the traffic and connectivity models in Subsections 2.2 and 2.3, the co-relation between them is summarized in Table 2.2.

Table 2.2: Co-relation between Traffic and Connectivity Models

Connectivity Model	Traffic	
	Density	Mobility
S2S	Low	Low
S2D	High	Low
D2D	High	High

2.4 Radio Propagation Model

The radio propagation is the behavior of radio waves when they are transmitted or propagated from one point to another one. The radio waves can be propagated through the earth surface or various level of atmosphere [58] [63]. In an area without any obstacle, both transmitter and receiver can connect without any interruptions. As a result, the radio wave is propagated along Line-of-Sight (LOS) as illustrated in Figure 2.3. While in an area with obstacles, the radio wave is propagated along Non-Line-of-Sight (NLOS) which is illustrated in Figure 2.3.

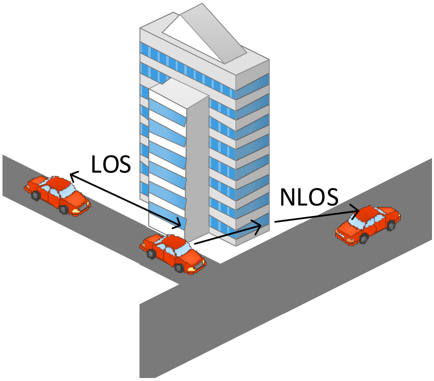


Figure 2.3: Line-of-Sight and Non-Line-of-Sight Propagation

A survey about IVC propagation explained that the propagation in large city environment is modeled as a NLOS [54]. In a large city environment, the basic issue of implementing a reliable connectivity in a real road topology is signal interferences. The signal interference due to common objects in a large city such as buildings, vehicles, tunnels, trees, and overpasses, spans on the road. When the signal is propagated through those objects, the signal behavior can be classified as the following: [63]

- reflection, on a smooth surface
- refraction, on small surface
- diffraction, around sharp edges
- absorption, transmission through object with a massive attenuation
- scattering, through rough surface

The first example, when the signal is propagated through the building, the signal at the receiver is the result of a reflection/refraction/diffraction phenomena. The second example, when a high vehicle, *i.e.,* a truck, will partially cover other vehicles' sight. With this condition, when the vehicle is located behind that truck, the propagated signal is considered as an attenuated signal. The second example is the condition of a vehicle that acts as a dynamic obstacle. Since this thesis does not discuss the exposure of car body metal [9], thus, the interference of other participating vehicles is considered as an insignificant factor in the transmission process.

Looking at a 3-dimensional case, objects are considered as the construction of a cross overpass, and a building between a parallel overpass as illustrated in Figure 2.2. The obstacle fading model is a type propagation model, where the existence of a concrete block, for example, being under the overpass, will attenuate or even restrict the signal transmission and reception. In a city environment where LOS model is not possible due to the exposure of physical obstructions and distance, the Nakagami fading model is used to represent signal receptions under conditions such as scattering, diffraction, and reflection [73]. Figure 2.4 shows Nakagami's probability of reception with a 500 m communication range. It indicates that the probability of successful reception of the signal is a decreasing function of the distance. Another propagation model for a city scenario is a radio ray tracing model [80]. This propagation model reflects the accuracy of signal reflection on a building's material which is defined in its reflection index. However, gathering information on building's material, shape, and its reflection resulting in almost impossible tasks due to a very computational cost. Therefore, because of resource and time constrains, the Nakagami model is used.

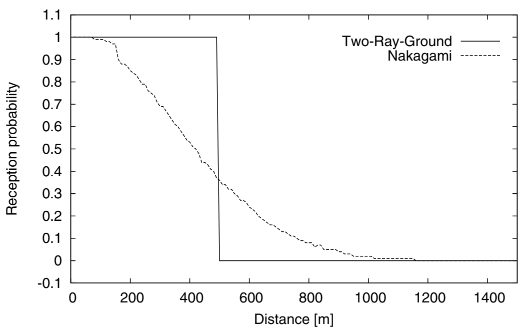


Figure 2.4: Probability of Reception for Two-Ray Ground and Nakagami Models [73]

Transmission Range A 2-dimensional area refers to an Euclidean area, which leads to inaccuracies of 3-dimensional modeling. In a 2-dimensional area, the vehicle's transmission range is usually modeled as a Unit Disc Graph (UDG), while in a 3-dimensional area, the vehicle's transmission range is modeled as a Unit Ball Graph (UBG). With an assumption that on the road, transmission pattern of a sphere will be 'cut', as the material of road will attenuate the signal strength, the UBG is set as half sphere to represent the transmission range between two mobile nodes. The transmission range in half sphere between two mobile nodes overlaps as shown in Figure 2.5

The transmission range of a vehicle is defined as the Connection Range (CR), the Detection Range (DR), and the Interference Range (IR), [63]. The CR is considered as the best range of connection between two communicating vehicles. Within the CR range, inter-vehicle connectivity is expected to be optimum. Although the CR is the best transmission range, the interference occurs occasionally due to several influencing attenuation. In [64] shows that the degraded communication range is 50% to 70%, thus, to gain the successful transmission, the CR is considered as a preferred transmission range within the radius of 200 m, while the DR is considered as a moderate transmission with lower interference compared to the IR. The attenuation as mentioned in Section 2.4, contributes to forwarding decision strategy which will be explained in Section 3.2.

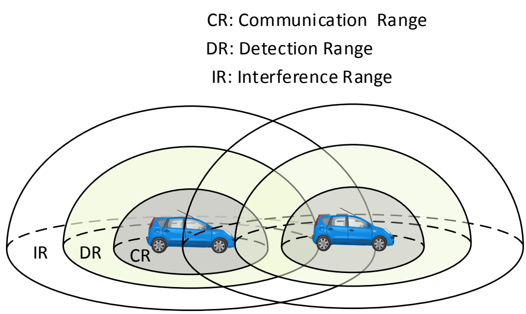


Figure 2.5: Transmission Range in Half Spheres

2.5 Discussion

The external factors have the significant impact in designing and improving a reliable IVC in a 3-dimensional case. Those factors represent the challenges that should be overcome in establishing the reliable IVC, as indicated in the following:

- Obstacles: the overpass construction and buildings are considered as inevitable physical obstructions. Those obstructions have an impact to the signal propagation and the probability of reception. Thus, the obstacles become the first challenge. However, the influence of the human exposure: human's body, and dynamic obstacles: a truck, are not considered.

- Distance: the vehicle's location coordinates is used to calculate the distance of two corresponding vehicles. This distance is analyzed and provides the information to a forwarding scheme. The forwarding scheme will decide which participating vehicles that would be the intermediate vehicle to forward the packet. The distance becomes the second challenge, because most of the IVC-based simulations oversimplify a 3-dimensional case onto a 2-dimensional case, ignoring the additional parameter: the elevation.

- Velocity. Since a vehicle is considered in a moving phase, therefore, the vehicle's velocity is one factor that influences the forwarding decision. Because, when the velocity of vehicles increase, the more frequent the change of network topology. Thus, the velocity becomes the third challenge.

- Duration of connectivity. The link connection refers to the duration of a successful transmission between two communicating vehicles. Thus, it become the fourth challenge to maintain the longer duration of connection among the communicating vehicles.

The realistic large city scenario in this thesis is defined based on the detailed consideration of all factors. Those factors are required to reflect the realistic environment and condition in a large city-based road topology.

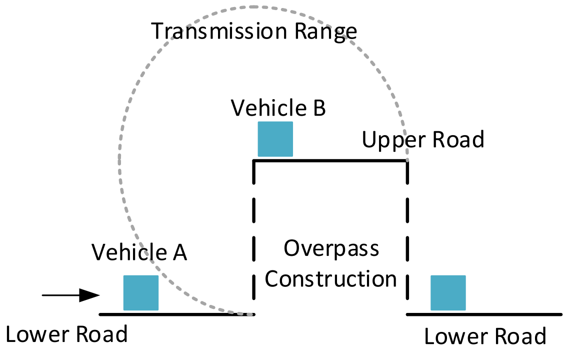


Figure 2.6: Expected Range Scheme

Figure 2.6 illustrates the overpass construction, the vehicle A which is located on the lower road, and the vehicle B which is located on the upper road. The vehicle B has the transmission range along with the interference from the overpass construction. Thus, the transmission range of the vehicle B will be attenuated as discussed in section 2.4.

The vehicle A that moves onto overpass construction is expected to have a blocked transmission range of the vehicle B. Although the transmission is not fully blocked, it is important to consider that the signal is in an attenuation condition. The illustration in Figure 2.6 is simulated in this thesis to validate the pre-mentioned external factors.

3

Design of a Forwarding Scheme for a Three-dimensional Environment

The key point of designing a forwarding scheme is the knowledge of IVC external factors which have been explained in Chapter 2. Those factors define the fundamental issues in IVC [17], which are necessary to be taken into consideration for deciding on the forwarding approach. Besides those external factors, there is another factor of importance. This factor describes several internal components that are applied to build reliable IVC, particularly in its forwarding scheme.

IVC internal components describe significant units to build connectivity among vehicles. These IVC internal components are classified based on their purposes which refer to the first three layers of the TCP/IP protocol stack: the physical, the MAC, and the network layers. The physical and MAC layers are represented in the inter-vehicular communication technology, and the network layer is represented in the forwarding strategy. IVC internal components are defined in Figure 3.1 and are further described in detail in Subsections 3.1 and 3.2.

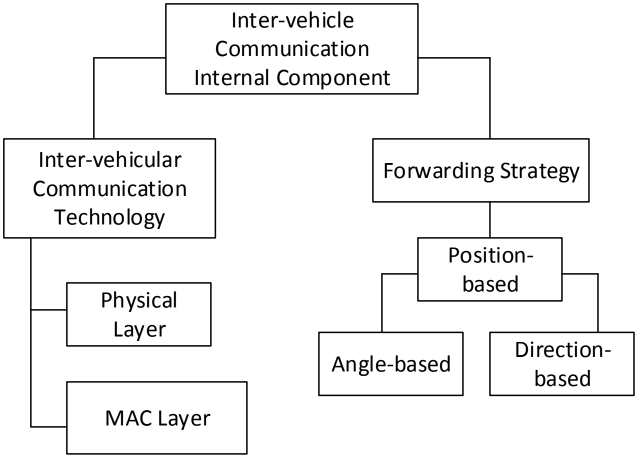


Figure 3.1: The Internal Component Requirement in IVC

3.1 Inter-vehicular Communication Technology

One of the important components in developing IVC is the inter-vehicular technology. Several inter-vehicle technologies have been developed as options for providing a better connection. These options include the wireless fidelity (WiFi) [14] [5], the worldwide interoperability for microwave access (WiMAX) [53], and the dedicated short range communication (DSRC)[72]. Those technologies define key functionality of the physical and the medium acces control (MAC) layers. The physical layer defines the type of antenna and the wireless local area network (WLAN) technoloy, featuring IEEE 802.11, which are discussed in Subsection 3.1.1. The MAC layer defines the channel protocol to manage the high mobility and topology variation [3], which is discussed in Subsection 3.1.2.

3.1.1 Physical Layer

The study of antenna radiation patterns has been done to prove that different type of antennas have an impact to the IVC performance. On one hand, the pattern of the antenna radiation impact to its placement and configuration [19]. On the other hand, this radiation pattern can impact to a bandwidth capacity [60]. Although there are two types of antenna: the omni-directional antenna and the directional antenna, the commonly used of antenna in IVC is the omni-directional antenna. The main reason is that the omni-directional antenna has the spectrum radiation pattern in uniform distribution. The omni-directional antenna which is used in this thesis has the spectrum radiation as shown in Figure 3.2 [63], [47]. Thus, for instance, the Wi-Fi transmission range of 300 m [45], are evenly distributed with the same signal strength [66], [45]. Based on the omni-directional antenna radiation, the connectivity range is expected to reach the horizontal and vertical communications.

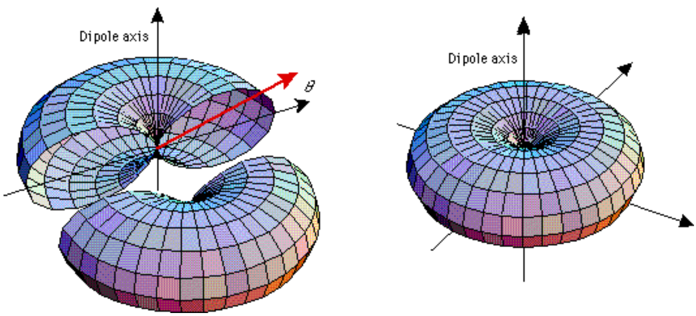


Figure 3.2: Omni-Antenna Spectrum Radiation [47]

The IEEE 802.11 working group has developed the standardization of the wireless technology. There are several IEEE 802.11 standards in a mass market, depending on its functionality. At the physical layer, for instance, the IEEE 802.11g is used for WLAN and allocated at 2.4 GHz, with the orthogonal frequency- division multiplexing (OFDM) that supports up to 54 Mbps [33]. Currently IVC technology uses IEEE 802.11p which is operated at the unlicensed 5.85–5.925 GHz ITS band in the United States and the newly allocated 5.855–5.905 GHz band in Europe [33]. This operating frequency is targeted at vehicular environment.

The implementation of IEEE 802.11p in IVC is to address the IVC's challenges: to accommodate a longer communication distance. In fact, IEEE 802.11p can provide IVC in ranges up to 1000 m [29]. A numerous researches on IEEE 802.11p Wireless Access in Vehicular Environments (WAVE) standard [19], spans from an intersection road topology [15] to a highway [51]. Moreover, the experimental studies show that IEEE 802.11p is also used to establish a safety [19] and a non-safety applications [3]. The further details on how the shared communication channel in IVC is divided, Subsection 3.1.2 describes the MAC layer and its channel modeling.

3.1.2 MAC layer

On top of the physical layer, IEEE 802.11p MAC layer is specified here due to channel modeling and data rate in IVC. IEEE 802.11p MAC has the capacity of addressing the frequent handshakes and authorization due to the fast movement and frequent topology changes in IVC [29]. Basically, IEEE 802.11p MAC is divided in seven channels, each channel with approximately 10 MHz bandwidth [77]. This division is based on the different utilities. The channels available in IEEE 802.11p is shown in Figure 3.3.

Several studies in IEEE 802.11p MAC investigate its deployment in safety [8] and non-safety applications [16]. In this thesis, IEEE 802.11p MAC is deployed in a non-safety application, thus, it works on channel number 172 and 174, and operates at 5.855-5.875 Hz.

3.1.3 Discussion

The Omni-directional Antenna

The current research and simulation in IVC use the directional antenna because it performs a maximum beam range: narrow and longer radiation pattern [60], [4]. The active beam forming as a result of directional an-

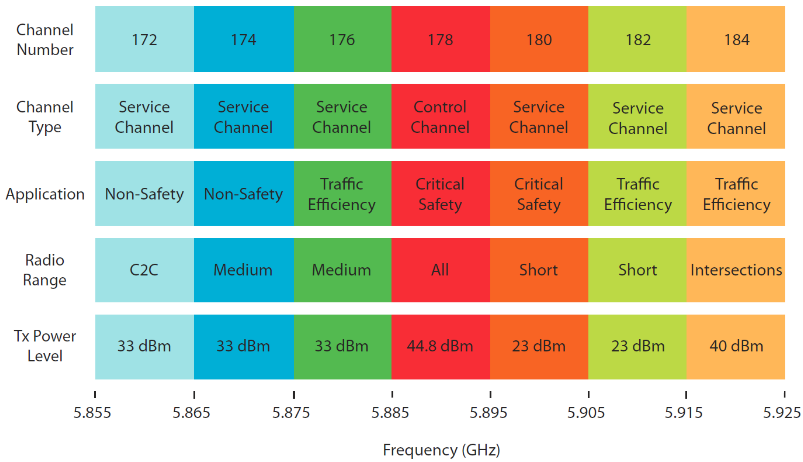


Figure 3.3: The IEEE 802.11p Channels Division [28]

tenna. However, the deployment of the omni-directional antenna is still feasible due to these following reasons:

- It does not need to adjust and do the calibration due to the uniform distribution beam width. In the directional antenna, the orientation of the antenna beam width has to be adjusted to obtain the optimal propagation [60].

- The direction of vehicles in a complex road topology can be more various: there are 4 directions in an intersection. Therefore, implementing the directional antenna increases the complexity in placing the antenna beam to a certain direction [60].

- In addition, the uniform beam width is propagated in the same signal strength. As a consequence, all participating vehicles at any positions within the sender's transmission range will receive the signal. Therefore, this uniform distribution beam width is suitable for investigating the proposed forwarding scheme.

Feasibility of Wi-Fi in Inter-vehicle Communication

Although for IVC IEEE 802.11p defines the technology standard, it is necessary to define other IEEE 802.11 derivatives as the continuity of IVC development, especially the possibility of installing Wi-Fi IEEE 802.11a/b/g/n in a public transportation determines a promising approach. The other reasons of Wi-Fi utility in IVC include:

- In an economic point of view, this opportunity of Wi-Fi utility becomes the first option since the rate of DSRC market penetration in several developing countries such in Indonesia is very low. This is shown that the Intelligent Transportation System (ITS) in Jakarta, Indonesia has just started in 2011 [70]. Moreover, the existence of WiFi as another IVC technology [53] also provides the potential utilization. The empirical experiment shows the possible communication by re-using the installed Wi-Fi to provide inter-vehicular connectivity and media distribution.

- In a social point of view, the intention to provide the internet connection in buses in order to encourage people to use public transportation instead of private vehicle. However, Wi-Fi utilization in public transportation is still an open research since it has not been evaluated in real road condition.

- In a technology point of view, the utility of Wi-Fi faces an issue of transmission coverage. This issue has been investigated since the Wi-Fi technology has poor performance under the massive obstacles as well as in the high speed. Massive obstacle influences the propagation transmission, while the high speed of vehicles leads to the frequent topology changes. Wi-fi is not designed to immediately recover for the new connection. The re-connection process increases the delay and bandwidth [13]. The evaluated WiFi technology emanates a hard hand off challenges. However, in a particular condition *i.e.,* specific velocity, Wi-Fi can be used as a practical communication [75], and also can be used to facilitate IVC up to 150 mph [75]

3.2 Forwarding Strategy-The Network Layer

The network layer is responsible for packet forwarding. As another IVC internal component, the forwarding strategy is the further step in the network layer to find a route from a source to a destination point. Thus, in most researches, the term packet forwarding strategy and routing protocol are used interchangeably. This thesis uses the term packet forwarding strategy.

To achieve a good connectivity in IVC, an efficient forwarding scheme must have the knowledge of participating vehicles. The knowledge of vehicles' position is utilized to establish a route in a reliable path [7]. Thus, promising forwarding schemes are those that take into account the position of vehicles.

A position-based forwarding scheme is considered as a well-applicable forwarding in the IVC [22], [7], [36], [38]. With the GPS [76] or Gallileo [2] assistance, a forwarding scheme can avoid a global route from a source to a destination [25]. The position-based forwarding scheme assumes that the location coordinate of a particular vehicle is available and always reachable by a source vehicle. In a real traffic environment, vehicles are spread over in a 3-dimensional area, therefore, the position-based forwarding scheme in the 3-dimensional area are an appropriate approach.

Advantage of Position-based Forwarding Scheme

Due to the frequent topology changes in IVC, the position-based forwarding scheme has several advantages are summarized in the following:

- No global knowledge is required: the position-based forwarding scheme is a one-hop forwarding, thus, a data packet is forwarded at the time a source identifies the location coordinates of its neighbor [48].

- No global forwarding table is required. Since the position-based forwarding scheme do not have the global route, it does not need to maintain a forwarding table [37], instead, to maintain the local forwarding table which is the list of neighbors' coordinate position.

- Scalable: the position-based forwarding scheme can handle a numerous participating vehicles and cope a wider area because it relies on the local position at given time [1].

- Adaptable: the position-based forwarding scheme relies on the location information. Thus, it is adaptable to find a dynamic forwarding path due to topology changes [38].

Several studies in position-based forwarding schemes shows the approaches in improving the forwarding schemes due to the large city environment: the 3-dimensional area, the vehicle positioning, and the traffic condition as discussed in Chapter 2. The improvement in a forwarding scheme is based on particular scenarios: at intersection road topology [69], [38] or a highway [22], a safety [11] or a non-safety application [49].

In the position-based forwarding scheme, there is a preliminary step so called as a searching mechanism. The searching mechanism is the process of a vehicle for finding positions of its neighbors. The algorithm of searching mechanism relies on the current location of participating vehicles. The position of the neighbor as well as the additional information such as speeds, a current distance and direction, are aggregated through one hop beacon which is transmitted periodically by all participating vehicles [48]. The next step of the position-based forwarding scheme is the forwarding decision. This forwarding decision depends on various approaches: in a dense IVC network, it should consider to restrict the area of forwarding [68], [67], or in a high mobility IVC network, it should consider the current direction of participating vehicles [11].

The prominent forwarding schemes based on geographic or location information are Greedy Perimeter Stateless Routing (GPSR) [39] and Greedy Perimeter Coordinator Routing (GPCR)[48]. By adding improvements on those position-based forwarding schemes, thus, it is expected to be well-suited for IVC implementations. In the greedy-based forwarding mechanism, a distance is the main factor that obtains the closest range of two communicating vehicles as shown in Figure 3.4 [39]. The distance factor is highly influenced by the velocity: speed and direction of vehicles.

In one hand, if the distance factor is combined with speed factor, the lifetime connection will have a linear value with the speed factor. On the other hand, if the distance factor is combined with the direction factor, it will have the denser or sparser position between two communicating vehicles. Figure 3.4 illustrates three basic types of forwarding schemes: the most forwarding scheme (MFS), the near forwarding scheme (NFS), and the angle forwarding scheme (AFS).

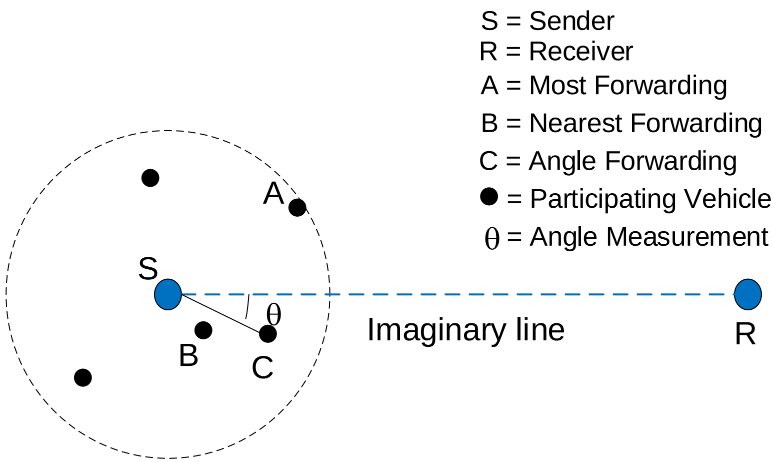


Figure 3.4: Three Basic Forwarding Schemes

3.2.1 Most Forwarding Scheme

The most forwarding scheme (MFS) calculates the path from vehicle S to its neighbors in order to obtain the best path to vehicle R. The common way of forwarding method calculates the distance from S to R. In the calculation process, the imaginary line is formed between S and R, the intermediate vehicle (I) is selected because I has the closest distance to R within transmission range of S. S will select vehicle A as the intermediate vehicle because vehicle A fulfill the fore mentioned requirement. By maximizing the distance of transmission, the MFS has an advantage of minimizing the number of hop. In this scheme, all vehicles have the same transmission range without concerning about the signal strength. The signal strength is considered as the uniform distribution pattern as indicated in Subsection 3.2. Therefore, this scheme is well-suited for reducing number of hops.

3.2.2 Near Forwarding Scheme

Basically, the near forwarding scheme (NFS) is the 'opponent' of MFS, since vehicle I is selected because vehicle I has the closest distance to vehicle S. NFS is indicated by the vehicle B as shown in Figure 3.4. This scheme is suitable for participating vehicles with various signal strengths, as a consequence, it is necessary to adjust the transmission power to reach the neighbors. Therefore, NFS is suitable for energy constraint forwarding scheme, to ensure the higher PDR.

3.2.3 Angle Forwarding Scheme

This forwarding scheme relies on angle calculation. The initial phase of an angle calculation is to determine the imaginary line, which is similar to MFS and NFS. The maginary line is a guidance line with vehicle S as a reference point. Based on the imaginary line, the angle forwarding scheme (AFS) provides additional measurement metric which is known as the relative angle. In order to obtain a proper angle calculation, it is necessary to discuss how the angle is measured. The determination of the imaginary line and the relative angle are described in the following:

Imaginary line: The dimension of transmission area can be a 2-dimensional and a 3-dimensional as discussed in Chapter 2. In case of a road with the 3-dimensional property, location information includes latitude, longitude, and altitude, which can be represented as x, y, and z-axis in Cartesian as mentioned in Subsection 2.1.2.

The imaginary line which is formed between S and R , represents in two lines i.e., k and j. The j line is formed between S and R based on x and y-axis, while k line is formed between S and R based on z, y and x-axis. Therefore, the location coordinate of S and R are $S(x_S, y_S)$ and $R(x_R, y_R)$ in two-dimensional area, while $S(x_S, y_S, z_S)$ and $R(x_R, y_R, z_R)$ in the 3-

dimensional area. Based on these location coordinates, the imaginary line can be defined as shown in Eq. 3.1

$$\theta = \arccos\left(\frac{(\vec{SR}).(\vec{SR})}{(|SR|)x(|SR|)}\right) \tag{3.1}$$

Relative Angle: Since various dimension of areas are considered, relative-angles in degrees are measured in two ways: First, it is measured between the positive x-axis and positive y-axis, which results in $\theta\ x$ while the second angle θz is measured between positive z-axis. This relative angle measurement becomes more valid when vehicle S is located on upper road level and vehicle R is located on lower road level. The measurement of relative angle is illustrated in Figure 3.5.

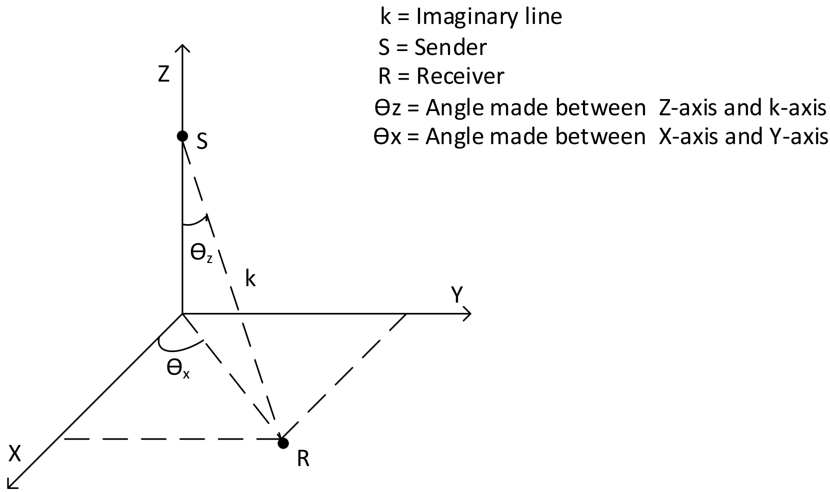


Figure 3.5: Relative Angle Measurement

Several researches based on AFS are classified based on the strategy to cope IVC external factor. These strategies are described in the following points:

- **Candidate Restriction**, this type of AFS restricts the number of candidates vehicles. The selected vehicle satisfies the smallest angle value. The illustration of candidate restriction scheme is shown in Figure 3.6.

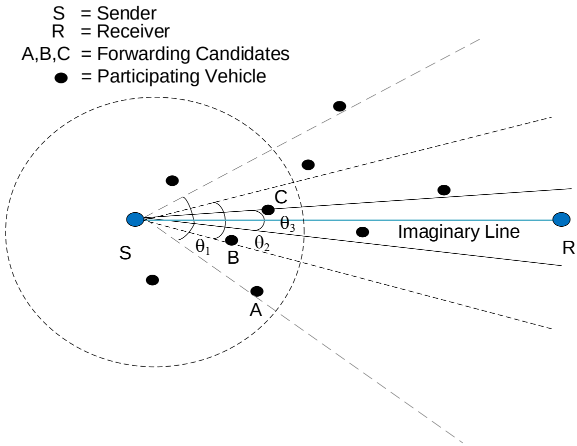


Figure 3.6: Candidate Restriction

- **Area Clustering**, the area of forwarding is clustered into several parts as illustrated in Figure 3.7. Thus, the forwarding scheme only works on the selected cluster.

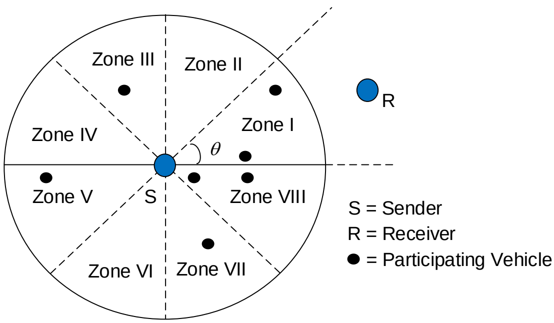


Figure 3.7: Area Clustering

- **Movement Prediction**, this type of AFS as illustrated in Figure 3.8, covers the issue of frequent movement in IVS. By measuring the relative angle of participating vehicles, the intermediate vehicle is expected to have the same direction with the destination.

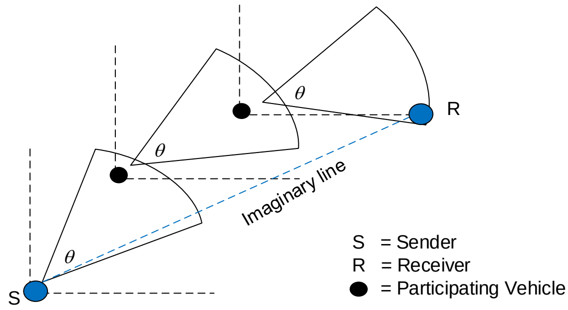


Figure 3.8: Movement Prediction

- **Void Avoidance**, the void problem occurs very often in a sparse environment. Thus, the idea of this AFS is to adjust the relative angle measurement. This adjustment is important to define the next forwarding vehicle that also has the next forwarding vehicle, by measuring two or more relative angles. If the first angle calculation does not cover the forwarder, then, the algorithm switches to the second angle calculation which is expected to cover the next forwarder. This scheme works if the current vehicle can find the next forwarding vehicle to the destination with the additional information of a next forwarder's neighbor as illustrated in Figure 3.9.

Table 3.1 shows the classification of angle forwarding schemes which are implemented in mostly 3-dimensional environments.

It is obvious that the existing angle-based forwarding schemes have several approaches depend on particular use case. This work focuses on angle-based forwarding scheme in a 3-dimensional environment, thus, it requires a special consideration as further discussed in Chapter 4 to emphasize the state-of-the art.

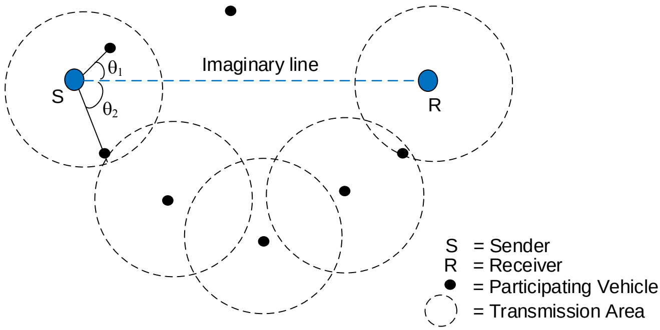


Figure 3.9: Void Avoidance

Table 3.1: Comparison of Angle-based Forwarding Schemes [42]

IVC External Factor	Angle-based Forwarding Scheme			
	Candidate Restriction	Area Clustering	Movement Prediction	Void Avoidance
Sparse Network	No	No	No	Yes
Dense Network	Yes	Partially	Partially	No
2-D Area	Partially	Yes	Partially	Partially
3-D Area	Partially	No	Partially	Partially
High Mobility	No	No	Yes	Partially
Low Mobility	No	No	No	Yes
Random Direction	Partially	Yes	Yes	Partially
Random Direction	Partially	Partially	No	No

3.3 Horizontal Relative Angle and Vertical Relative Angle

Further facts in determining the transmission range is to take into account the impact of the Horizontal Relative Angle (HRA) and the Vertical Relative Angle (VRA). Thus, the evaluation is done by several parameters that lead to the significant value in setting the height and θ. In order to calculate the number of participating vehicles at time t, the participating vehicles are restricted based on the θ and height parameter. These parameters are set to determine the real width and height of a city road. For instance, the road with the width of 20 m and the height of overpass is 10 m. Thus, the θ is set to 60° from the point of S which is located on the middle of overpass.

Figure 3.10, indicates the position of vehicle S at t_x will have two distances to vehicle A as indicated by the position of A and A'. In case of the range of HRA and VRA becomes a probability of distribution, thus, the nakagami propagation model is used.

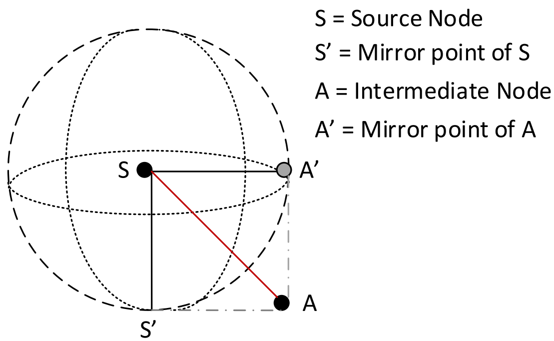


Figure 3.10: Different Ranges of HRA and VRA

The last key point of designing is related to ensure the clear result between VRA and HRA. For instance, vehicle S is the source with transmission range as shown by dashed sphere area in Figure 3.10, vehicle A is the intermediate vehicle. Since the Wi-Fi transmission range is assumed as transmission area of S, thus, vehicle A is actually out of vehicle S' transmission range, even the position of A is located at A' when it is viewed from above. This is why the 3-dimensional point of view is important.

It is also necessary to consider various heights and widths of the road due to signal transmission and reception. A current vehicle and an intermediate vehicle on different road levels (i.e. vehicles on upper road layer and lower road layer) can create an angle between them as illustrated in Figure 3.5. Angles in degrees are measured in two ways: Firstly, it is measured between the positive x-axis and positive y-axis, which results in θx. Secondly, the angle θz is measured between the positive z-axis and the coordinate of a vehicle which is located on lower layer road as illustrated in Figure 3.11. The θz angle influences the transmission range between vehicles on upper and lower road levels. In order to simplify and clearly describe the two communicating vehicles, the vehicle S is a vehicle, moving on the upper road

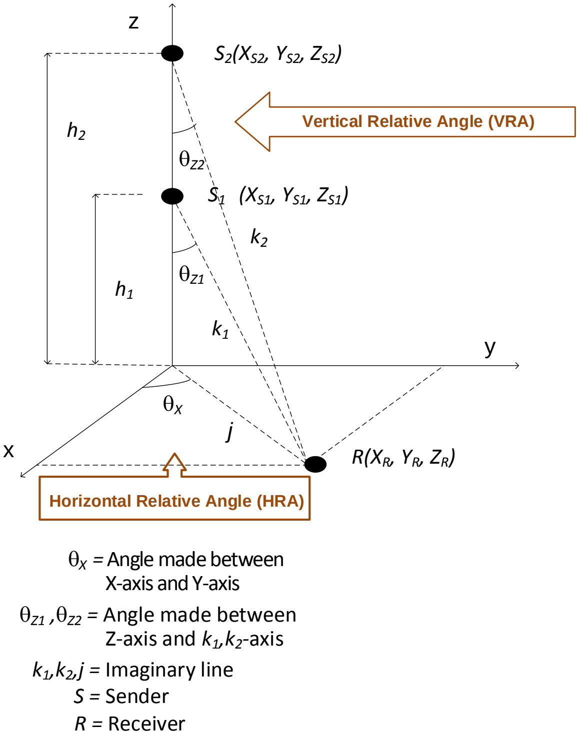


Figure 3.11: Two Relative Angles Measurement

level, thus, it forms an angle θz with respect to the vehicle R, a vehicle that is moving on the lower road layer.

Proposed 3-dimensional Forwarding Scheme

The proposed forwarding scheme is to provide the realistic detail in multiple dimensions. In most researches and studies in IVC, the existing forwarding methods can only be applied in the 2-dimensional case, which means neglecting the third coordinates *i.e.,* the altitude or elevation. VRA forwarding scheme implements the minimum and maximum angle denoted as θ min and θ max. These angles determine which participating vehicle becomes the next intermediate vehicle. The preference area of the VRA forwarding scheme is located within θ min and θ max. Thus, VRA scheme will only transmit packets if the intermediate vehicles are within this particular area.

When two vehicles are located at different road levels, the road construction in-between can be considered as an obstacle (Chapter 2). Thus, it is almost impossible to forward the packet successfully because that obstacle interfering the transmission signal as discusses in Chapter 2, Subsection 2.4. Introducing VRA as the new parameter is expected to measure the realistic and practical transmission areas. Therefore, VRA is considered as the additional weight value and the signal strength measurement in a 3-dimensional case. The design of the proposed scheme will be discussed in detail in Chapter 4.

4

Vehicular-to-vehicular Urban Network Forwarding Scheme

The HRA and VRA metrics have been introduced in order to improve a 3-dimensional forwarding scheme. This section describes further refinements of HRA and VRA for several use cases in a large city scenario, which is defined as the Vehicular-to-vehicular Urban Network (V2VUNet).

4.1 Architecture of The Vehicle-to-vehicle Urban Network

The V2VUNet determines a proposed improvement to the traditional position-based forwarding scheme that address forwarding issues in the 3-dimensional environment. The main goal of the V2VUNet is to ensure that the proposed forwarding scheme applicable in a 3-dimensional area: detects the proper vehicles' position, especially at the *z*-axis, and improves the traditional forwarding scheme in particular use cases.

By recalling from Subsection 3.2, GPSR is selected because it represents the greedy position-based forwarding scheme. The additional location coordinate, the altitude z-axis, is added to ensure that GPSR is applicable in the 3-dimensional scenario. To understand the greedy position-based forwarding scheme, there are three mandatory steps, which are described in the following:

- The first step is to get hold of the location coordinates of vehicles. It is assumed that the location provider installed in each vehicle, gathers vehicle's location coordinates. The vehicle at time t located in the location coordinate of x, y, z-axis.

- The second step covers the process to collect all information of participating vehicles are known. These information include the position and the velocity of participating vehicles. Given all determined information, the sender does not need to build a global forwarding path to the destination, instead, gathers all the local required information from its neighbors.

- The third step runs the calculation of the imaginary line from the sender to the predefined receiver, as previously discussed in Subsection 3.2.3.

In general, a position-based forwarding scheme defines three components as indicated in 4.1 and works as follows:

- **Relay Selection**, defines metrics that are used in order to decide the participating vehicle as the intermediate vehicle or the next relay. Metrics in this relay selection step calculate several variables: the distance from a sender to a receiver, the angle that relevant to the distance, and the velocity which includes the path direction to the receiver.

- **Forwarding Strategy**, determines a method to forward the packet after the next relay has been selected. Two greedy-based methods are used to forward the packet. One greedy method, selecting the

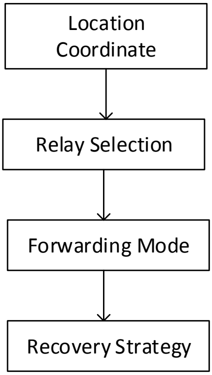


Figure 4.1: A Position-based Algorithm in General

next relay, which is located closer to the origin sender, the other method, selecting the next relay which is located closer to the destination. Both methods have particular advantage: the relay selection that closer to the destination intents to minimize the number of hops. The relay selection that closer to the source intents to minimize the energy consumption, which is also to address the uneven transmission range issue.

- **Recovery Strategy**, is required due to the classic greedy issue: a local maximum, which is the condition where unavailability of a relay candidate that is located closer to the receiver, except the sender it self. Thus, a carry and forward mechanism is used. Since the carry and forward mechanism also causes longer delays, some algorithms add the path recalculation.

Referring to GPSR, these are several 3-dimensional forwarding strategies, which strongly related to V2VUNet.

3DGR - a position-based forwarding scheme in a static scenario, with a minimum transmission distance in order to reduce the energy consumption [78]. This forwarding scheme works in a WSN.

TDR - a position-based forwarding scheme in a VANET [46]. However, this forwarding scheme does not emphasize the loss connection in the different road levels transmission. Thus, the 3-dimensional scenario is oversimplified.

C-TDR - a position-based forwarding scheme which is the TDR's development for a complex 3-dimensional scenario [31]. The range transmission model is fluctuating but it is not clearly described how the vehicle obtains this fluctuating transmission range. The C-TDR algorithm describes the complex 3-dimensional scenario, however, the propagation model does not reflect the realistic complexity of road topology.

V2VUNet - a position-based forwarding scheme in IVC [43]. It clearly indicates that the transmission range is fluctuating due to the overpass construction. It is also defined in propagation model for a large city scenario, which more explicitly defines the 'blocking' mode for less connectivity. The V2VUNet is more practical when it is applied in a real city scenario since it uses the interactive world map: OpenStreetMap (OSM) [50], to obtain movement data from user. When a blocking condition is detected in the 3-dimensional area, the V2VUNet applies the predictive mode to address the inevitable obstruction issue. The architecture of V2VUNet refers to the traditional position-based algorithm (cf. Figure 4.1), which is illustrated in Figure 4.2.

State-of-the Art

Among the 2- and 3-dimensional forwarding schemes as previously discussed, V2VUNet works on both 2- and 3-dimensional road topologies. As illustrated in Figure 4.2, the blue boxes indicate the V2VUNet's state-of-the art: the 3-dimensional awareness. This 3-dimensional awareness of V2VUNet is described by the following five key points:

- V2VUNet applies the 3-dimensional road topology detection, as indicated by the z-axis.

- V2VUNet applies the angle measurement with the relative direction awareness. Thus, the relative angle measurement can improve the vehicle's positioning.

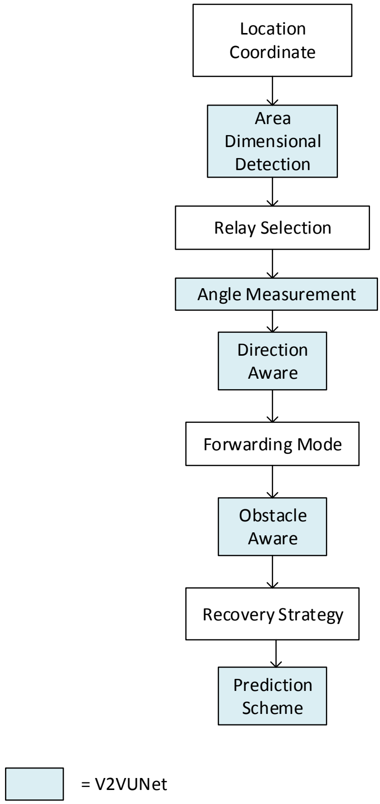


Figure 4.2: V2VUNet Architecture

- V2VUNet applies the 'blocking' mode due to the overpass construction as indicated in the obstacle awareness, which is very practical in a real implementation.
- V2VUNet applies the prediction scheme to address the 'blocking' issue.
- V2VUNet is applicable for any position-based forwarding schemes, since it works on top of searching algorithm.

The comparison of those pre-mentioned 3-dimensional forwarding schemes is provided in Table 4.1

Table 4.1: Comparison of 3-dimensional forwarding scheme

Forwarding Scheme	3-DGR	TGR	C-TDR	V2VUNet
Mobility	Static	Non-static	Non-static	Static and non-static
Network Type	WSN	VANET	VANET	VANET-IVC
3-D Scenario	Simple	Simple	Less complex	More complex
Propagation	LOS	Two-ray ground	Two-ray ground	Nakagami Obstacle awareness
Key Point	Energi awareness	avoid 3-D path	no-recovery mode	3-D awareness mode

Basically, V2VUNet can be implemented on any position-based forwarding schemes. V2VUNet defines several additional steps in a position-based forwarding scheme, as indicated by blue boxes in Figure 4.2. The first step of V2VUNet shows the area dimensional detection, which defines working areas: 2-dimensional or 3-dimensional area. The HRA and VRA calculation, which are distinguished by the z-axis value. Figure 4.3 shows a simple algorithm to decide the further calculation for HRA and VRA.

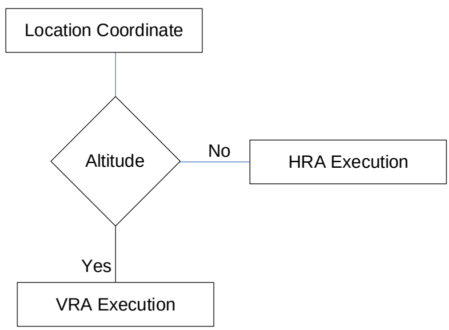


Figure 4.3: The Area Dimensional Detection Algorithm to Distinguish HRA and VRA Execution

For a simple V2VUNet implementation, Figure 4.4 illustrates the 3-dimensional use case with cross and parallel overpasses. The HRA calculation is fulfilled when both sender and receiver are located at the same road level, and further discussed in Section 4.3. In case of VRA, both sender and receiver are located at the different road levels, and further discussed in 4.4.

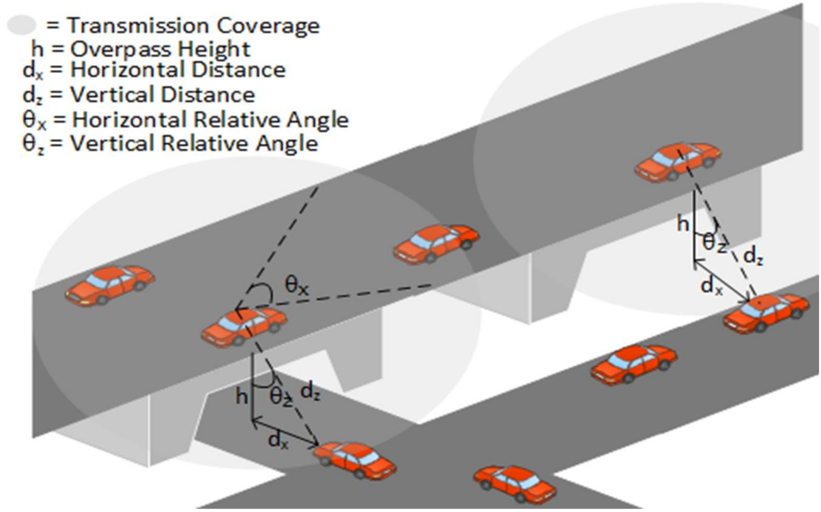


Figure 4.4: 3-dimensional Analysis

4.2 Forwarding Decision Analysis

The concept of V2VUNet combines a greedy-based forwarding with angle-based forwarding scheme. It means that the angle-based and the greedy-based forwarding scheme are applied in a process of selecting the relay vehicle. The greedy-based forwarding scheme is applied to a relay vehicle that has the closest distance to the receiver. This angle-based forwarding scheme is applicable for vehicle's location coordinates on top of other vehicle's location coordinates. This condition has been neglected at most studies and simulations although it has a significant impact in the real experiments.

4.3 Horizontal Relative Angle Analysis

The Horizontal Relative Angle (HRA) is the angle value that is produced by measuring two vehicles with the support of an imaginary line. The imaginary line is determined as a line drawn between a sender and a receiver. The forwarding decision is based on the measured HRA which basically selects the smallest angle value. This smallest value of HRA is applied to ensure that the relay vehicle is located as close as possible to the sender. The smallest value of HRA can maintain the homogeneity of lane direction. The homogeneity of a lane direction is assumed that vehicles are located close to the imaginary line. Therefore, the effort of searching and forwarding a packet in the area that is restricted by the smallest angle value, requires less time than in the area without a restriction.

4.4 Vertical Relative Angle Analysis

The Vertical Relative Angle (VRA) shows a similar measuring method with HRA except, VRA is implemented in a 3-dimensional area. The smallest VRA value is applied to ensure that a relay vehicle maintains the connection life time between two vehicles. The VRA improves the forwarding scheme by determining the relay vehicle in a sender's transmission area. VRA can be defined based on its functionality in two approaches. The first approach when VRA is combined with a distance weight value and the second one when VRA is combined with a velocity weight value. The first approach is the combination between the VRA and the distance weight value. As a result, the VRA can be applied to restrict the area of transmission, similar to the HRA. The second approach is the combination between the VRA and the velocity weight value. As a result, the VRA can be applied to predict the movement of participating vehicles. Both approaches are discussed in Section 4.5.

4.5 Implementation of V2VUNet

V2VUNet is implemented in an urban/city environment. The possible implementation of V2VUNet is shown in providing non-safety applications in the public transportation. The V2VUNet is expected to guarantee a reliable connectivity, while transmitting the large data packet. However, since it is not designed for a safety application, thus, the delay can be assumed as fairly acceptable by the user. The implementation of V2VUNet is described in the following approaches:

4.5.1 Area Restriction Approach

The area restriction approach is the concept of selecting the best participating vehicle as the relay or intermediate vehicle. Considering the dense network as described in Subsection 2.2.1, the participating vehicles might act as the connection 'supporter' or the relay, or as the connection 'blocker'. This area restriction approach has to look at the speed and direction of each participating vehicles within the source's transmission range. In the area restriction approach as indicated in Alg. 1, the V2VUNet operates in two steps. The first step is to determine HRA preliminary value of 30° as indicated in Alg. 1, line 4: $\theta_{x,max}$, which is intuitively based on the width of a road in a 2-dimensional area. The second step is to adjust HRA based on the available participating vehicles' position as indicated in Alg. 1, line 9: $I_{filtered}$. The V2VUNet algorithm selects the relay vehicle based on the smallest value of HRA, among all participating vehicles.

Those two steps in HRA are also applied in the 3-dimensional area, thus, it is similar to HRA, VRA is determined of 30° value. The 30° value is determined based on the cosine rule in Eq. 4.5. The width of road is set to 8 meters to reflect the width of roads in Jakarta on average, which is shown in Figure 4.5. The first step, the angle value of 30° is set to indicate the preliminary angle value based on the transmission range. The result of 14.93 meters (cf. Figure 4.5) defines CR, which is discussed in Subsection 2.4. Thus, this 30° angle value is tuned based on the road width, which is denoted in Alg. 1, line 5: $\theta_{z,min}$. This 30° value is then increased gradually as

Algorithm 1 Area Restriction Forwarding Scheme

1: $S \leftarrow$ Sender Vehicle
2: $R \leftarrow$ Receiver Vehicle
3: $I \leftarrow$ All Participating Vehicles of S at position p_i, Orientation v_i
4: $\theta_{x,max} \leftarrow$ maximum boundary of the horizontal angle, tuned heuristically based on the road width
5: $\theta_{z,min} \leftarrow$ minimum boundary of the vertical angle, tuned heuristically based on the road width
6: $\theta_{z,max} \leftarrow$ maximum boundary of the vertical angle, tuned heuristically based on the road width
7: $\theta_x \leftarrow$ horizontal angle made by I to S
8: $\theta_z \leftarrow$ vertical angle made by I to S
9: $I_{filtered} \leftarrow$ only I that is within $\left[-\theta_{x,\,max}, \theta_{x,\,max}\right]$ and $\left[-\theta_{z,\,min}, \theta_{z,\,max}\right]$
10: $d \leftarrow$ distance from $I_{filtered}$ to R
11: $Nexthop \leftarrow \arg min\ (d)$

part of the searching mechanism, as indicated in Alg. 1, line 6: $\theta_{z,max}$. The second step, the area restriction mechanism is applied as indicated in Alg. 1, line 9: $I_{filtered}$. The area restriction mechanism will iterate in case there is no vehicle that fulfills the requirement.

$$\cos(A) = \frac{b^2 + c^2 - a^2}{2bc} \tag{4.1}$$

4.5.2 Predictive Forwarding Approach

In the predictive forwarding approach, HRA is used to predict the direction of participating vehicles. The prediction algorithm is designed to address the disconnection issues due to the transmission range in the 2-dimensional area. In case of VRA, it is designed to address the disconnection issue due to obstructions: the overpass construction on a cross overpass topology, and the building between a parallel overpass topology. For the sake of a precise prediction, the direction which is measured in HRA and VRA, is determined as a relative direction. The relative direction esti-

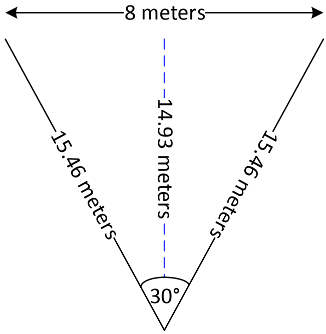


Figure 4.5: The Cosine Rule

mates the actual direction in the 3-dimensional scheme, which is changed whenever a vehicle changes its position as illustrated in Figure 4.6.

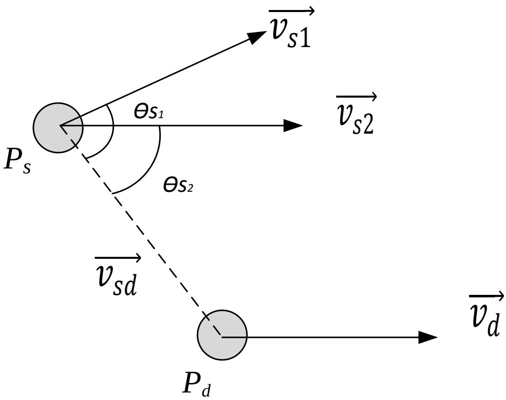


Figure 4.6: Relative Direction of Two Vehicles

For instance, the vehicle S at position P_s has the angle value of θ_{S1} if it is measured when vehicle S is moving at direction V_{S1}. Thus, the measurement of angle values depends on the orientation of each vehicle. As a consequence, the traditional direction calculation cannot be implemented in this prediction scheme.

Algorithm 2 Path Prediction Scheme

1: $S \leftarrow$ Sender Vehicle at position of p_s, orientation of v_s
2: $I \leftarrow$ All Participating Vehicles of S at position p_i, Orientation v_i
3: $\theta_{solid} \leftarrow$ Threshold of the Angle for All i
4: $v_{si} = \left|p_s - p_i\right|$
5: $\theta_{si} = atan\left(\left|\left|v_s \times v_{si}\right|\right|, \left|\left|v_s \cdot v_{si}\right|\right|\right)$
6: $I_{filtered} \leftarrow I$ with θ_{si} within $\left[-\theta_{solid}, \theta_{solid}\right]$
7: $d \leftarrow$ distance from $I_{filtered}$ to R
8: $NextHop \leftarrow argmin(d)$

The path prediction scheme is shown in Algorithm 2. The first step of this algorithm is to define the orientation of each participating vehicles I, including vehicle S, which is denoted in Alg. 2, line 1-2. The second step is to set the angle threshold of all participating vehicle, which is denoted in Alg. 2, line 3:θ_{solid}. This angle threshold is set to determine the forwarding area. The third step is to calculate the smallest angle value and select the best intermediate vehicle, as indicated in Alg. 2, line 5: θ_{si} and line 6: $I_{filtered}$, respectively. The path prediction scheme ensures that the intermediate vehicle moves in the same direction with the destination vehicle, such that, the selected intermediate vehicle will always move in the same direction with the destination vehicle.

Those two proposed algorithms are expected to provide a high network performance which is indicated by high PDR and low end-to-end (E2E) delays. To summarize all proposed algorithms in this thesis, Table 4.2 shows a comparison of the angle, area restricted, and path prediction forwarding schemes and indicates all related factors: the location coordinate, the weight value, the relative direction, the routing based, and the road topology.

The first factor in this comparison, the coordinate location, describes the coordinate axis, which is used in measuring the current location of a vehicle. The second factor is weight values, which determine angle calculation schemes: HRA for a 2-dimensional area and VRA for a 3-dimensional area. The third factor is the relative direction, which is added to the path prediction algorithm in order to improve the location coordinates calcula-

Table 4.2: Comparison of the Angle, Area Restricted, and Path Prediction Algorithms

Factor	Angle-based Forwarding	Area Restriction	Path Prediction
Location Coordinate	x-, y-axis	x-, y-, z-axis	x-, y-, z-axis
Weight Value	HRA	HRA VRA	HRA VRA
Relative Direction	No	No	Yes
Routing based	Greedy	Greedy	Greedy
Road Topology	2-D Intersection, Highway	3-D Intersection, 3-D Parallel	3-D Intersection, 3-D Parallel

tion. This relative direction factor is suitable when vehicles move at various directions, and is important to indicate the current direction of a vehicle. The greedy-based forwarding scheme is applied in all algorithms to determine that intermediate vehicle, which is close to the final destination. The last factor influencing all forwarding schemes is the road topology. The angle-based forwarding scheme is applied on the 2-dimensional intersection, where the direction factor becomes an important value, and on the highway, where the speed of vehicles is highly relevant. In addition, these road topology types lead to an improvement of the forwarding scheme, which can be applied on a complex road topology.

4.5.3 Enhanced V2VUNet for a Complex Road Topology

The idea of improving the V2VUNet is to combine the area restriction and prediction forwarding scheme. This enhanced V2VUNet is investigated to evaluate the advantage of the proposed forwarding schemes applied to more complex road topology as indicated in Figure 5.5 in Chapter 5. Basically this enhanced V2VUNet is aware of the width of the road, the restriction step as a part of area restriction algorithm, which is indicated in Alg. 3, line 3-6: $\theta_{h,max}$, $\theta_{v,\,min}$, and $\theta_{v,\,max}$, respectively. The initial HRA and VRA values of 30° are set as indicated in Alg. 3, line 6-7: θ_{hi}, and θ_{vi}.

These initial angle values are associated to the width of road: in this use case 8 m. Furthermore, the prediction step applies the relative direction to predict the vehicles' movement, which is discussed in Subsection 4.5.2, as indicated in Alg. 3, line 9-13. The detailed parameter settings and simulation environments of this complex road topology are described in Chapter 5.

Algorithm 3 Enhanced V2VUNet

1: $S \leftarrow$ Sender Node at position of p_s, orientation of v_s
2: $I \leftarrow$ All Neighboring Nodes of S at position p_i, Orientation v_i
3: $\theta_{h,max} \leftarrow$ Maximum boundary of the Horizontal Angle, tuned heuristically based on the road width
4: $\theta_{v,\, min} \leftarrow$ Minimum boundary of the Vertical Angle, tuned heuristically based on the road width
5: $\theta_{v,\, max} \leftarrow$ Maximum boundary of the Vertical Angle, tuned heuristically based on the road width
6: $\theta_{hi} \leftarrow$ Horizontal Angles, made by every I to S
7: $\theta_{vi} \leftarrow$ Vertical Angles, made by every I to S
8: $I_{filtered} \leftarrow I$ with θ_{hi} within $\left[\theta_{h,\, min}, \theta_{h,\, max}\right]$ and θ_{vi} within $\left[\theta_{v,\, min}, \theta_{v,\, max}\right]$
9: $I \leftarrow I_{filtered}$, all participating vehicles of S at position of p_i and orientation of v_i
10: $\theta_{solid} \leftarrow$ Threshold of the Angle for All i
11: $v_{si} = \left|p_s - p_i\right|$
12: $\theta_{si} = atan\left(\left|\left|v_s \times v_{si}\right|\right|, \left|\left|v_s \cdot v_{si}\right|\right|\right)$
13: $I_{filtered} \leftarrow I$ with θ_{si} within $\left[-\theta_{solid}, \theta_{solid}\right]$
14: $d \leftarrow$ distance from $I_{filtered}$ to R
15: $NextHop \leftarrow$ argmin (d)

4.6 Chapter Summary

This section refined the two proposed approaches in detail. The area restriction and the predictive forwarding scheme outline the forwarding strategy that takes into account HRA and VRA measurements. The main focus of the V2VUNet implementation is the 3-dimensional environment. The area restricted and the predictive forwarding schemes have been combined to the enhanced V2VUNet forwarding scheme in order to obtain the level of awareness in vehicle's direction as well as the area forwarding restriction.

The main contribution of the proposed approaches is to improve existing position-based forwarding schemes due to incompatible algorithms especially in the 3-dimensional environment. The measurable part of the main contribution is addressing the inevitable obstacles problems due to road topology construction. The idea of selecting the intermediate vehicle takes into account the presence of participating vehicles with proper radio propagation model and the best calculation of the relative angle. Finding the intermediate vehicle in the 3-dimensional area is performed based on the position of participating vehicles.

5
V2VUNet Simulation Model and Environment

The evaluation of the V2VUNet is conducted under a specific simulation environment. This chapter describes the wireless network device, simulator tools and their configurations, the parameter setting information, and selected results.

5.1 Obstacle Simulation Model

This obstacle environment model is required to investigate the existing obstruction made of the road construction which is located on top of first road level. The 3-dimensional environment model requires a reference model for the sake of an ideal comparison. As the first step, a 2-dimensional environment is set up to build the environment layout. This 2-dimensional layout is composed by x- and y-axis coordinates, thus, this road topology layout is settled as the first layer. Recall the relative angle calculation as previously described in Chapter 4, Section 4.3, the HRA calculation is applied is on this first layer.

The second step is to set the 3-dimensional layout. In order to generate it, the existing 2-dimensional coordinate location is then added with the third axis, *i.e.,* z-axis that represents the altitude. Thus, the 3-dimensional layout is composed by x-, y-, and z-axis coordinates, and is settled as the second layer. This 3-dimensional road topology layout is set on top of first layer, with two positions: the second road is laid and crossed to the first layer or is laid in parallel to the first layer, as shown in Figure 5.3.

The third step is to set the vehicle's coordinate location on both road layers. By adding z-axis, thus, the angle calculation becomes more complex in 3-dimensional. The VRA is calculated in this 3-dimensional environment, as previously described in Chapter 4, Section 4.4.

The complete parameters that are used in this preliminary 3-dimensional environment are shown in Table 6.1.

Table 5.1: Parameter of Obstacle Environment Scenario

Parameter	Value
IEEE 802.11a Transmission Range	up to 300 m
Number of Vehicles	10 - 40
Simulation Area	500 m x 500 m
Obstruction Height	10 m
Average Vehicle Velocity	30 km/h
Simulation Time	200 s
Number of Driving Lanes	2
Packet Size	512 Bytes
Antenna Model	Omniantenna

The simulation environment is required as the information that conveys to the complete results in Chapter 6. For this simulation, the layout is set in area size of 500 x 500 m, where a straight road with the simple cross overpass is placed, as illustrated in Figure 5.1.

Figure 5.2 shows the result of applying the obstruction and no-obstruction scenario in the nakagami propagation model. The cross overpass represents this obstruction scenario, thus, the overpass is simply block-

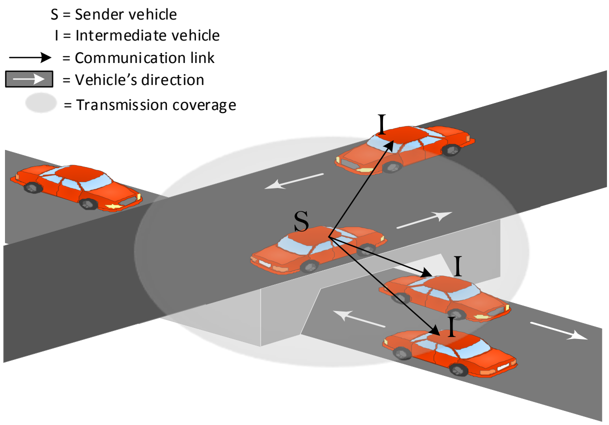


Figure 5.1: A Simple 3-dimensional Overpass

ing the signal transmission. In the area without an obstruction shows the better results compare to the area with an obstruction. To be more detail, the result shows that the area with an obstruction, the Packet Delivery Ratio (PDR) reach less than 30%. The PDR is decreasing as the number of vehicles is increasing. The area with an obstruction decreases the PDR up to 40%. Beside the PDR, the End-to-end (E2E) delays of the area with an obstruction increases from 15% - 30% compare to the area without an obstruction. On one hand, the E2E delay as a result of cumulative delays of participating vehicles is also increasing as the number of vehicles is increasing. On the other hand, one vehicle can handle multiple forwarding process, thus, this will lead to high delays. Both PDR and E2E delays have a poor performance, which is mainly because the obstruction. Thus, the overpass construction does impact to the network performance.

Based on that selected scenario and results, the next scenarios will be simulated based on the greedy forwarding as the forwarding scheme's reference as well as the inclusion of complex obstructions such as buildings and overpass in cross and parallel approaches.

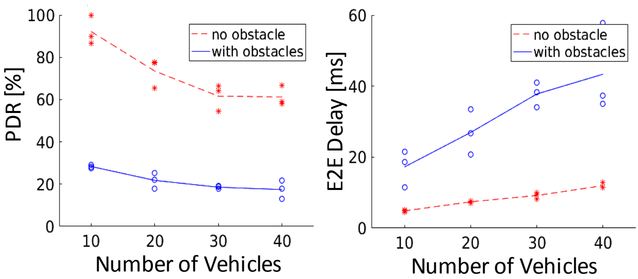


Figure 5.2: Impact of Overpass Construction

5.2 V2VUNet Scenario

The scenario of V2VUNet is running in two modes, the area restriction mode and the prediction mode. V2VUNet runs in a city scenario with an overpass construction, too. Due to the complexity of the city scenario, the overpass construction restricts the connection, which occurs in the two 3-dimensional scenarios, to a cross overpass and a parallel overpass. In one case, when S and R are located at the same coordinate of x and y, this position leads to the disconnection status for both S and R. In another case, when S and R are not located at the same coordinate of x or y, this position leads to the out-of-reach transmission range at some point.

5.3 Description and Environment

The 3-dimensional environment derives in two models, which reflect a real road environment in Jakarta. These two models are described in the following subsections.

5.3.1 Cross overpass model

The description of a cross overpass topology is illustrated in Figure 5.3. The layout for this model is set as a rectangle shape with the size of 1000 m x 500 m x 20 m. The rectangle shape illustrates a straight road with two lanes and an overpass construction in the middle of the road. The overpass' height is set as 20 m. The cross overpass is located in the middle of road to indicate the obstruction environment as previously mentioned in Section 5.1.

5.3.2 Parallel overpass model

The detail of this model is similar with the previous cross overpass model as illustrated in Figure 5.3. Two straight roads are separated in width of 50 m. However, this model applies the obstruction as a building which is located between those straight roads. In this model, there is no chance that vehicles are located at the same *x* and *y*-axis coordinates.

5.3.3 Ramp overpass model

This model is indicated by the increasing of road height gradually as illustrated in Figure 5.3. The road height that increases gradually indicates the impact of height to the connection life time between two communicating vehicles. The increment of the road height is set each 5 m above the ground level: 5 m, 10 m, 15 m, and 20 m.

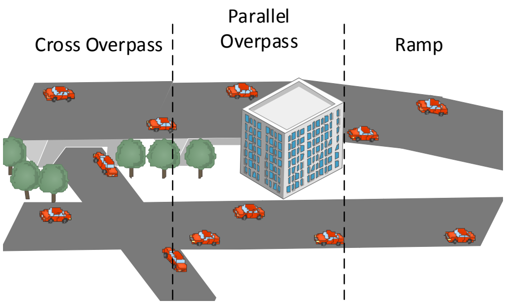


Figure 5.3: A 3-dimensional Road Topology Model

5.4 Communication Model

Participating vehicles are the vehicles that have connection process actively. The connection process is described in two phases: the connectivity build up and the main communication. The connectivity build up is the phase of interchanging the basic information: the location coordinates and the velocity. The main communication is the phase of interchanging the main information: Pairs of connections: the S and R are generated randomly, thus, all participating vehicles can be the sender, the receiver, and/or the intermediate vehicle. In addition, all S and R are placed randomly on both road levels. However, the direction of vehicles is set in the constrained trajectory, because vehicles have to follow the predefined driving lane. To investigate the connection life time among communicating vehicles the communication model type is described in Subsection 5.4.1, 5.4.2, and 5.4.3.

5.4.1 Static-to-static Vehicles

The Static-to-static (S2S) communication model refers to vehicles that communicate in a static mobility during the traffic jam when the mobility at the current time can drop to 0 m/s. The static mobility shows the path taken when the communication is established, occurs on the different road levels.

5.4.2 Static-to-dynamic Vehicles

This Static-to-dynamic (S2D) communication model refers to the pattern of communication during the moderate traffic. For instance, the traffic on the overpass runs swiftly, but on the underpass the traffic is jammed. Thus, it is important to investigate the communication life time in this communication model.

5.4.3 Dynamic-to-dynamic Vehicles

This Dynamic-to-dynamic (D2D) communication model evaluates the probability of loss connection when the high mobility of communicating vehicles on both road levels are applied. The mobility model are determined as slow, medium, and fast categories. This evaluation of applying various mobilities has the impact to frequent disconnection. Thus, this frequent disconnection leads to the new searching mechanism process.

5.5 Simulation Architecture

In order to simulate the forwarding schemes proposed, the simulation architecture is illustrated in Figure 5.4.

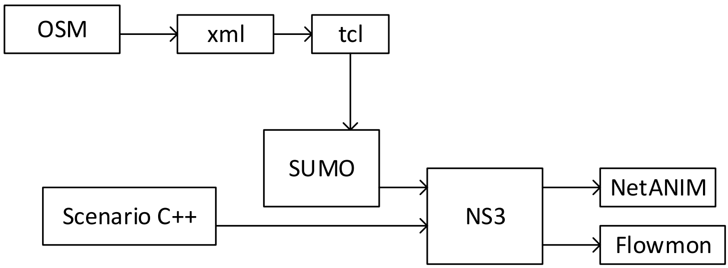


Figure 5.4: Simulation Architecture

5.5.1 OpenStreetMap (OSM)

The Open Street Map (OSM) ia an interactive world map which is collaborated by available users. The map data is collected from many contributors and it can be edited. The OSM of Jembatan Semanggi is captured and shown in Figure 5.5 [23]

The inclusion of the OSM is important in order to obtain the real measurement in realistic and complex traffic patterns. The data which is captured by OSM contains of elements such as vehicles, ways, areas, and relations [50]. Those elements are in the form of raw data and they are converted into file maps and stored as map.xml file. This xml file is converted to tcl file, thus, it can be read by SUMO.

5.5.2 Simulation of Urban MObility (SUMO)

The Simulation of Urban MObility (SUMO) [40] is one of the mobility generator that generates vehicles' mobility with micro and macro mobility

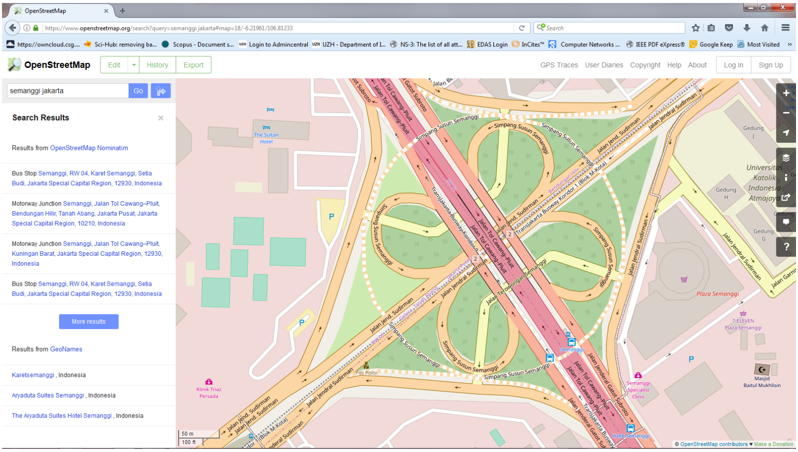


Figure 5.5: OSM Capture

models. SUMO has the Intelligent Driving Mobility (IDM) option to simulate the realistic vehicles' movement in particular road traffic. Figure 5.6 shows a trace file of the IDM which is generated by the SUMO in particular area. The mobility data which is captured by SUMO is stored as output.tcl file.

5.5.3 NS3

The Network Simulator 3 (NS3) is used [24] to simulate the overall scenarios. This work using NS3 version 2.35 under Linux platform: Ubuntu 14.04 in a virtual box. The mobility model is generated by SUMO which is fed to NS3 as the scenario simulator. To illustrate the communication process, the NetAnim [35] exhibits the animation as shown in Figure 5.7. NetAnim is an animation tool which is usually embedded in NS3 package. The NetAnim captures the simulation process only in the 2-dimensional environment. Therefore, 3-dimensional environment simulation process is not able to be captured. As a result, the different road level topologies do not appear in NetAnim. The result graphs are plotted using Matlab and

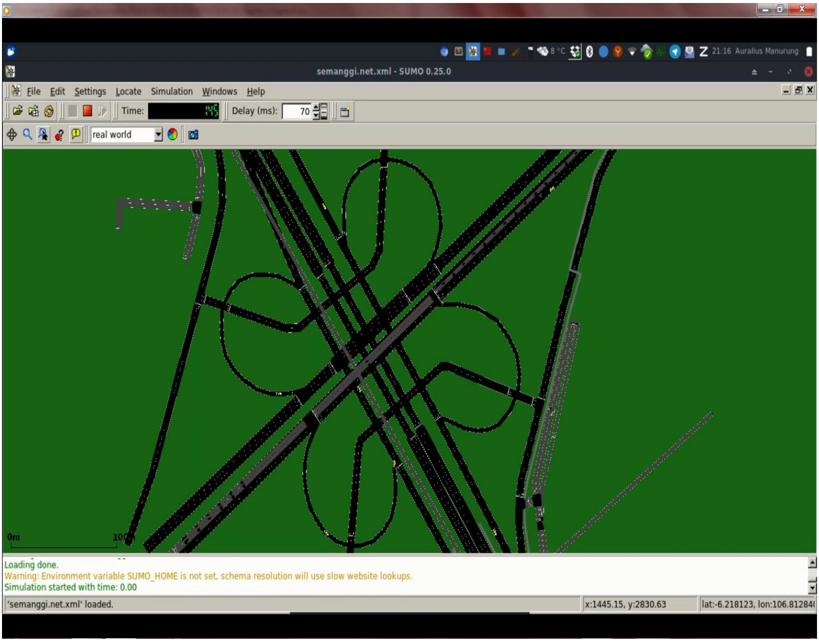


Figure 5.6: SUMO Capture

showed graph lines with error bars. The simulation for all scenarios are generated 30 times to reflect the daily pattern in a month.

5.6 Parameter environment

In general, the parameters in the simulation environment are shown in Table 6.1. Each parameter and its value which are defined based on the NS3 documentation[57], are described in the following:

- **Wireless Network Device**: modeled as an physical interface that takes care of transmitting and/or receiving signals from one device to other devices. The IVC uses the IEEE 802.11a and the IEEE 802.11p as the standard wireless network technologies. By default, the communication range of the IEEE 802.11a is set approximate up to 300

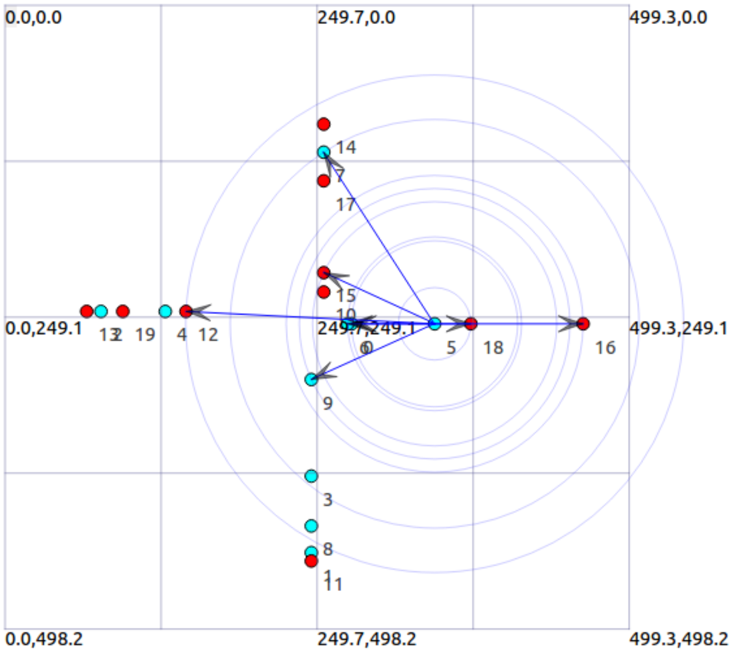
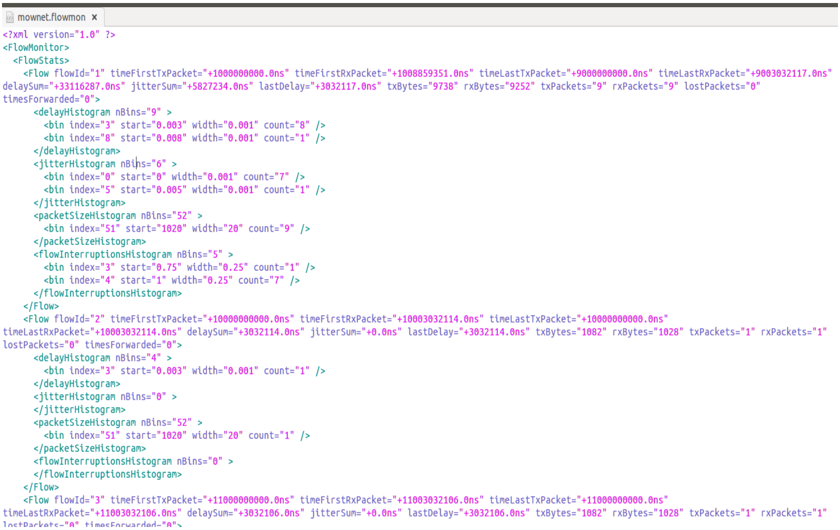


Figure 5.7: NetAnim Capture

m, and the communication range of IEEE 802.11p is approximately up to 1000 m. However, in this simulation the communication range of IEEE 802.11p is set at maximum 500 m with some losses due to the overpass construction. In the NS3, the IEEE 802.11 a/p are created under the class library `WifiDevice`. The IEEE 802.11p wireless technology is implemented in this work, however, in one use case, the IEEE 802.11a is used to investigate the impact of transmission range to packet forwarding.

- **Propagation Loss Model.** The default of propagation loss model based on the nakagami propagation model in city environment. This

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  <FlowStats>
    <Flow flowId="1" timeFirstTxPacket="+1000000000.0ns" timeFirstRxPacket="+1008859351.0ns" timeLastTxPacket="+9000000000.0ns" timeLastRxPacket="+9003032117.0ns"
delaySum="+33116287.0ns" jitterSum="+5827234.0ns" lastDelay="+3032117.0ns" txBytes="9738" rxBytes="9252" txPackets="9" rxPackets="9" lostPackets="0"
timesForwarded="0">
      <delayHistogram nBins="9" >
        <bin index="3" start="0.003" width="0.001" count="8" />
        <bin index="8" start="0.008" width="0.001" count="1" />
      </delayHistogram>
      <jitterHistogram nBins="6" >
        <bin index="0" start="0" width="0.001" count="7" />
        <bin index="5" start="0.005" width="0.001" count="1" />
      </jitterHistogram>
      <packetSizeHistogram nBins="52" >
        <bin index="51" start="1020" width="20" count="9" />
      </packetSizeHistogram>
      <flowInterruptionsHistogram nBins="5" >
        <bin index="3" start="0.75" width="0.25" count="1" />
        <bin index="4" start="1" width="0.25" count="7" />
      </flowInterruptionsHistogram>
    </Flow>
    <Flow flowId="2" timeFirstTxPacket="+10000000000.0ns" timeFirstRxPacket="+10003032114.0ns" timeLastTxPacket="+10000000000.0ns"
timeLastRxPacket="+10003032114.0ns" delaySum="+3032114.0ns" jitterSum="+0.0ns" lastDelay="+3032114.0ns" txBytes="1082" rxBytes="1028" txPackets="1" rxPackets="1"
lostPackets="0" timesForwarded="0">
      <delayHistogram nBins="4" >
        <bin index="3" start="0.003" width="0.001" count="1" />
      </delayHistogram>
      <jitterHistogram nBins="0" >
      </jitterHistogram>
      <packetSizeHistogram nBins="52" >
        <bin index="51" start="1020" width="20" count="1" />
      </packetSizeHistogram>
      <flowInterruptionsHistogram nBins="0" >
      </flowInterruptionsHistogram>
    </Flow>
    <Flow flowId="3" timeFirstTxPacket="+11000000000.0ns" timeFirstRxPacket="+11003032106.0ns" timeLastTxPacket="+11000000000.0ns"
timeLastRxPacket="+11003032106.0ns" delaySum="+3032106.0ns" jitterSum="+0.0ns" lastDelay="+3032106.0ns" txBytes="1082" rxBytes="1028" txPackets="1" rxPackets="1"
lostPackets="0" timesForwarded="0">
```


Figure 5.8: Flowmon File

propagation loss model uses the default reference loss of 46.6777 dB at reference distance of 1 m.

- **Obstacle Model**: defines the obstruction of each road level. The obstruction is composed of concretes which is placed between first layer and second layer road topologies. This obstruction placement and composition are important to reflect the overpass construction. In the NS3, this obstruction is defined under the class `StoneBlocks` library, which can be configured to described the overpass dimensions [56].

- **Packet Size**: determines the number of packets that are transmitted. This packet size considers the number of bytes which are generated and sent in a period of time under the `classPacket` library in the NS3.

5.6.1 Complex Road Topology

In order to increase the complexity of roads, Figure 5.9 shows a map of roads: straight-shaped and non-straight-shaped roads. The non-straight road is important factor to determine a vehicle's position. The position determination indicates on which angle measurement is executed: the HRA and VRA.

Figure 5.9: A Complex Road Topology: Jembatan Semanggi, Jakarta, Indonesia [26]

In a complex road topology, the road topology is modeled with the various heights and road shapes. The main idea is to evaluate the enhanced V2VUNet: a combination of two forwarding approaches, in various road heights and shapes as indicated in Chapter 4. The complex road use case is taken from Semanggi bridge, jakarta, Indonesia, as illustrated in Figure 5.9. However, since the circle-shaped road of Figure 5.5 has not been inaugurated until August 17, 2017, thus, this work cannot obtain the real data of the circle-shaped road and the real mobility which is provided by active users has not available yet. To address this issue, the GPSies [27] is used to generate the mobility track on the predefined road.

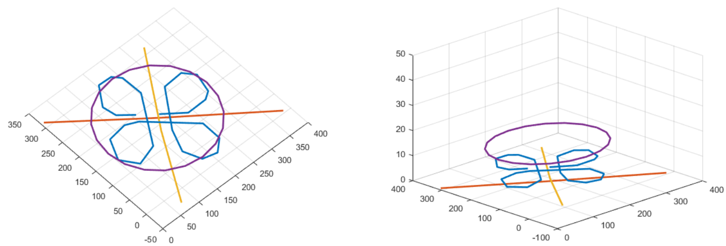

Figure 5.10: Four-layers Road Topology

This road topology has four road topology layers with different heights and it is modeled in a complex 3-dimensional point of view. These four layers reflect the realistic and updated road topology in Semanggi bridge. In addition to the four-layers road topology, the height of each layer is obtained from the following:

- The first layer of a straight road with the height of 0 m (ground level).
- The second layer of a cross overpass with the height of 5 m above the ground lever (first level).
- The third layer of a clover-shaped road with the height of 10 m (second level). Some parts of this clover-shaped road provides ramp and connects to the first layer.
- The fourth layer of a circle-shaped road with the height of 15 m (third level). This circle-shaped road is modeled to reflect the circle path without considering the ramp road which is linked to other roads. The idea is to simplify the ramp road model since SUMO does not support the 3-dimensional mobility.

6 Evaluations and Results

Two approaches of the 3-dimensional forwarding scheme in V2VUNet is evaluated under scenarios, that span from a simple scenario to a complex one. The following sections indicate the results in specific scenarios based on parameter settings such as number of participating vehicles, mobility models, and packet sizes. In addition, the V2VUNet simulations run in 30 times to reflect the monthly 30 working days.

6.1 Overpass Impact Analysis

Based on the previous initial result as presented in Chapter 5, this simulation investigate the impact of obstructions. The parameter of obstruction environment scenario is shown in Table 6.1. Respective results are illustrated in Figure 6.1 and Figure 6.2. They indicate that the overpass construction influence the inter-vehicle connectivity.

The first set of results in Figure 6.1 shows the impact of obstructions to the network performance. The solid line illustrates the performance that

Table 6.1: Parameters of Obstruction Environment Scenario

Parameter	Value
IEEE 802.11a Transmission Range	up to 300 m
Number of Vehicles	20 – 100
Simulation Area	500 m x 500 m
Obstruction Height	10 – 20 m
Average Low Vehicle Velocity	30 km/h
Average High Vehicle Velocity	70 km/h
Simulation Time	200 s
Number of Driving Lanes	2
Data Rate Model	CBR 54 Mbps
Packet Size	512 Byte

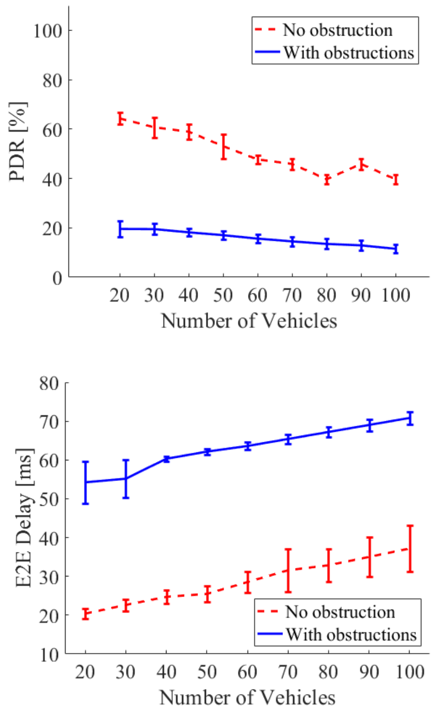

Figure 6.1: Impact of Obstructions in Low Speed

includes the existence of an obstruction and compares to the dashed line, which illustrates the performance without an obstruction. This evaluation applies two speeds: 30 km/h that reflects the low speed and 70 km/h in a large city is considered as the high speed. The highest obtained PDR with an obstruction in the low speed is 20%, which is considerably low. This low PDR is caused by the overpass construction and buildings. The overpass construction which is added between two different levels of roads, block the signal reception partially. Thus, the traditional position forwarding scheme has a difficulty to find the "undetected" vehicles, which is located under the overpass. The E2E delays shown from 55 ms to 70 ms, which indicate that the number of vehicles increase the time needed for forwarding the packet. The increased delay occurs due to the decision process of the intermediate vehicle. This delay is the common issue in the traditional position-based forwarding scheme. For example, the delay will increase when there is no intermediate vehicle that fulfills the requirement.

The second set of results in Figure 6.2 shows the network performance which is simulated under the speed of 70 km/h.The PDR with the impact obstruction shows only 25%. The similar reason as described previously that the low PDR is caused by the inevitable obstructions. The obstruction blocks the connection between two communicating vehicles, thus in case of low speeds, one of two communicating vehicle is located in a 'blind' spot, *i.e.*, it is unreachable by other vehicles. The E2E delays increase from 20 ms to 60 ms due to the frequent disconnection in a high speed. Thus, this clearly indicates that the re-searching mechanism of position forwarding take longer times. From those results, it proves that neglecting the obstruction impact, especially in the 3-dimensional environment will not have the valid measurement, as previously discussed in Subsection 2.1.

The simulation of a 3-dimensional road topology is proceeded with different heights of overpass. The results are shown in Figure 6.3 and 6.4.

The third set of results as shown in Figure 6.3, indicate the network performance under the various road heights: z = 10 m , 15 m, and 20 m, under the low speed. The overpass' height of 10 m shows the highest PDR compared to other overpass' heights: 15 m and 20 m. From the PDR and E2E delay results, these indicate that the higher the overpass, the network

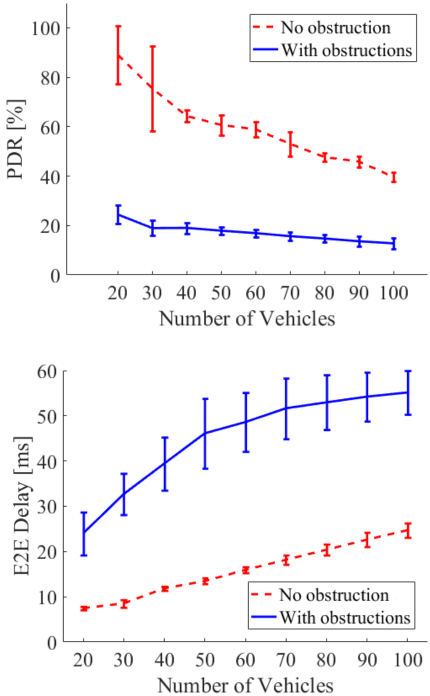

Figure 6.2: Impact of Obstructions in High Speed

performance becomes lower. These results validate a proof of concept of the 3-dimensional topology: the height of road topology, as previously discussed in Subsection 3.3. Under the higher speed, the PDR with the overpass' height of 10 m shows the stable degradation, but still shows the highest PDR compared to other PDR with the higher overpass. This result also shows that the higher the second road topology level, leads to the higher chance of disconnection due to the transmission range.

The fourth set of results which is related to a different road level topology *i.e.*, vehicles located both on overpass and under overpass, is shown in Figure 6.5. The life time connections among vehicles on the same altitude (*i.e.*, road level) have the longer duration than on the different altitude. This indicates that the altitude factor cannot be neglected, since the sender select the intermediate vehicle within the connection range (CR), as previously

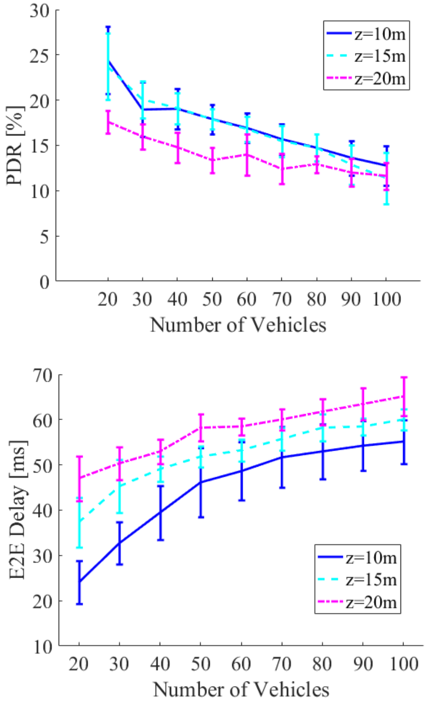

Figure 6.3: Impact of Different Heights of Road Topology in Low Mobility

discussed in Subsection 2.4. Practically, the results of life time connection can be used in the real city scenario.

Due to those findings, the following evaluations will take into account the obstruction model as the consequences of a realistic 3-dimensional road topology in the large city environment.

6.2 V2VUNet-Area Restriction

The first forwarding scheme approach, the area restriction in V2VUNet, is evaluated under the parameter and environment as shown in Table 6.2.

In this simulation, the traditional position-based forwarding scheme is compared to the area-restriction forwarding scheme. The traditional

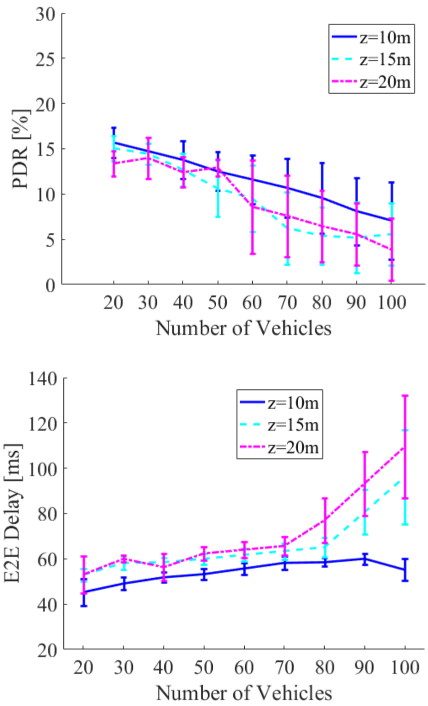

Figure 6.4: Impact of Different Heights of Road Topology in High Mobility

Table 6.2: Parameters of Area Restriction Evaluation

Parameter	Value
IEEE 802.11a Transmission Range	up to 300 m
IEEE 802.11p Transmission Range	up to 1000 m
Number of Vehicles	20 – 40
Simulation Area	1000 m x 500 m
Obstruction Height	10 m
Average Vehicle Velocity	40 – 70 km/h
Simulation Time	200 s
Number of Driving Lanes	2
Packet Size	1024 Byte

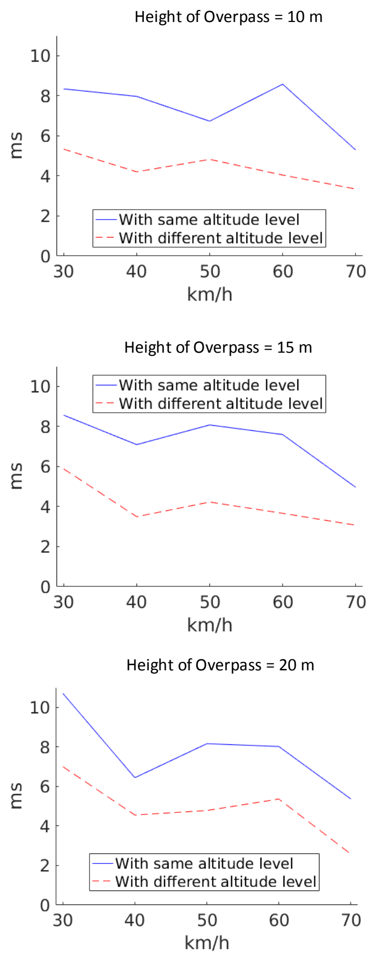

Figure 6.5: Connection Life Time

position-based forwarding scheme which is described in Subsection 3.2, applies the position coordinates to forward the packet without any improvements.

In the 3-dimensional environment, the feasibility of using the IVC wireless devices depends on their transmission range. The evaluation of the IEEE 802.11a and IEEE 802.11a is described in Subsection 6.2.1.

6.2.1 The IEEE 802.11a and IEEE 802.11p

To investigate the two well-known technologies in the IVC, this thesis applies the IEEE 802.11a and the IEEE 802.11p in this simulation. The results are illustrated in Figures 6.6 and 6.7

The solid blue lines indicate the result of area restriction forwarding scheme implementation. The dashed red lines indicate the traditional position-based forwarding scheme without implementing the area restriction forwarding scheme. The PDR of each applied speed shows that the area restriction reveals the better result compared to the forwarding scheme without the area restriction scheme. This indicates that involving the relative angles: the HRA and VRA, as the additional metrics to the forwarding scheme is necessary to determine the proper intermediate vehicles out of available participating vehicles. The area restriction algorithm reduces the number of unnecessary participating vehicles using the HRA and VRA calculation. The highest PDR shows 20% using the IEEE 802.11a and 30% using the IEEE 802.11p, which is also considerably low due to the obstruction scenario. Another reason of low PDR is caused by the overpass construction scenario that dominates the simulation area. Moreover, the speeds being used in this simulation are the maximum speed that can be reached by vehicles, such that vehicles are moving at speed from 1 km/h to maximum 40 km/h. Thus, the IEEE 802.11p results do not have the clear effect in terms of communication range. Overall, the PDR is decreasing due to the higher speed of vehicles which lead to frequent disconnections.

However, the E2E delay considered has to be handled as a trade-off. The E2E delay shows fluctuating results as shown in Figure 6.7, and has larger delays on average. The speed of vehicles has an insignificant impact to these E2E delays. Thus, the delay reached determines the result of the forwarding scheme, searching for the new connection or path once the current path is disconnected or broken.

Although the transmission range of IEEE 802.11p can be set up to 1000 meters and much higher than the IEEE 802.11a, this cross overpass scenario with the obstruction causes the poor result of PDR. The IEEE 802.11p works as expected in terms of distance when the simulation area

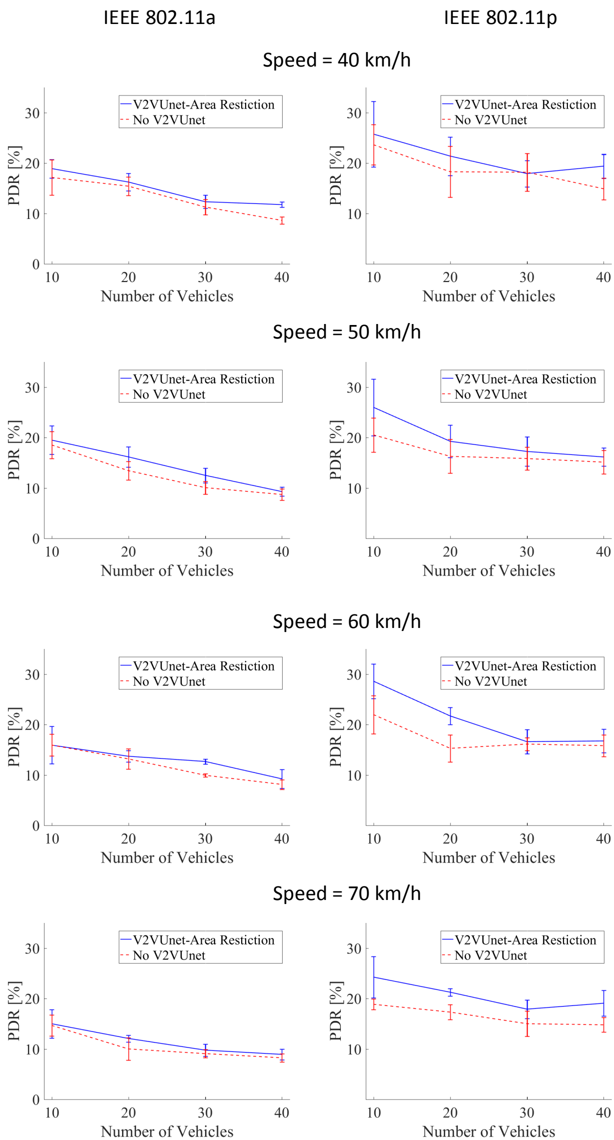

Figure 6.6: V2VUNet-Area Restriction Performance Using IEEE 802.11a/p

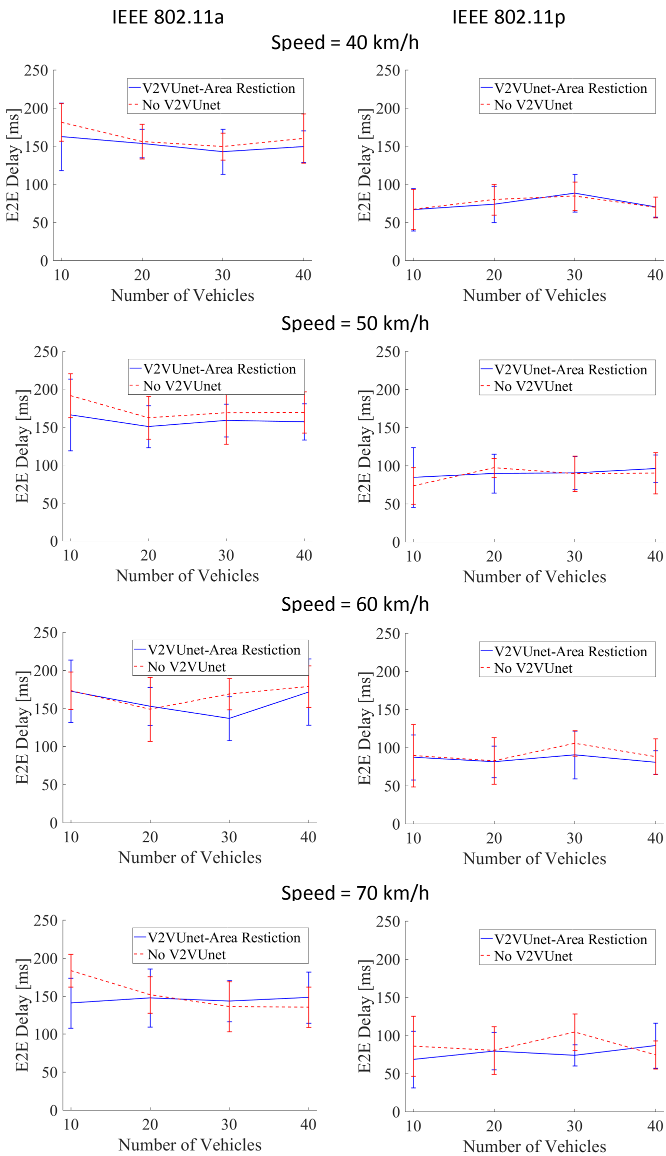

Figure 6.7: V2VUNet-Area Restriction Delay Using IEEE 802.11a/p

is in Line-of-Sight condition such as on the highway. From those PDR results for both IEEE 802.11a and IEEE 802.11p do not have much difference in this obstruction use case. Thus, the IEEE 802.11p with 1000 meters transmission distance setting is unnecessary in this obstruction use case. In addition, it is reasonable to determine that the IEEE 802.11a is still feasible to be applied in this use case, as previously discussed in Subsection 3.1.3. Since the IEEE 802.11p shows better results compared to the IEEE 802.11a, therefore, it is more reasonable to apply the IEEE 802.11p as the IVC's wireless device in the next following evaluations.

6.2.2 Cross and Parallel Overpass Scenario

The second evaluation of the area restriction forwarding scheme is run on a road with the cross and parallel overpass on the top of it. The results of the cross and parallel overpass scenarios are shown in Figure 6.8 and 6.9.

This simulation is deploying the IEEE 802.11p, as previously discussed. The solid blue lines indicate the result of the area restriction forwarding scheme, which is denoted as "V2VUNet-Area Restriction", and the red dashed lines indicate the result of the traditional position-based forwarding scheme, which is denoted as "No V2VUNet". The PDR results of the area restriction forwarding scheme show slightly better than the traditional position-based forwarding scheme as illustrated in Figure 6.8. The highest PDR in the cross overpass scenario is 30% and in the parallel overpass scenario is 90%. From all PDR results, the performance are almost 10% to 15% better than the traditional position-based forwarding scheme.

The E2E delays of the area restriction forwarding scheme are almost similar with the E2E delays of the traditional position-based forwarding scheme. Thus, the area restriction forwarding scheme improves the PDR in both cross overpass and parallel overpass scenarios.

6.2.3 Inter-vehicle Communication Models

This simulation evaluates the inter-vehicle communication models: Static-to-Dynamic (S2D), and Dynamic-to-Dynamic (D2D). On one hand, the S2D model reflects the condition where some of participating vehicles are

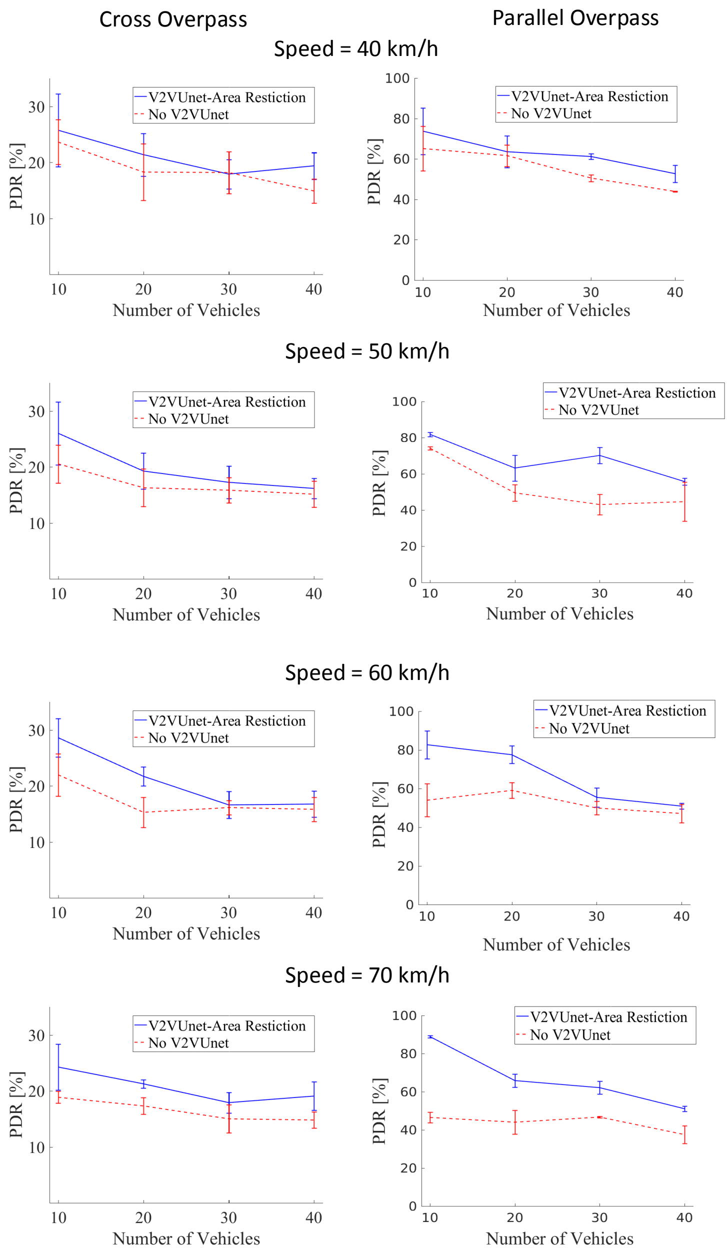

Figure 6.8: V2VUNet-Area Restriction in Cross and Parallel Overpass Scenarios

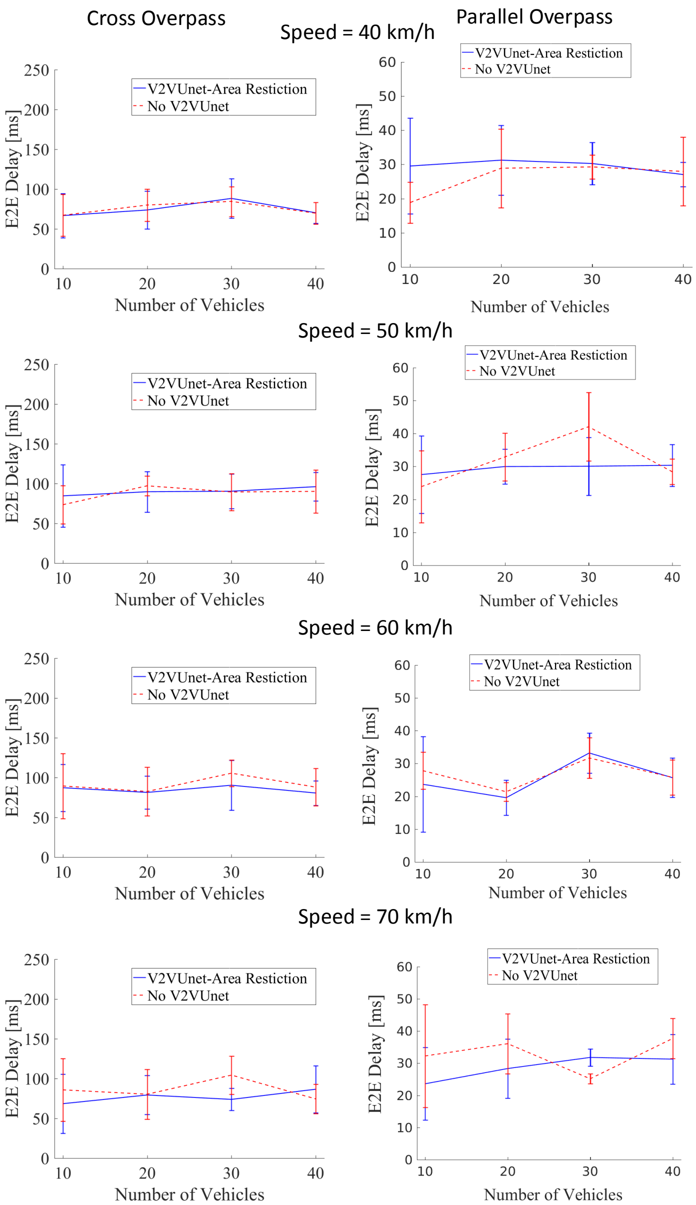

Figure 6.9: Delay of V2VUNet-Area Restriction in Cross and Parallel Overpass Scenarios

not moving due to traffic jam. On the other hand, the D2D model assumes that all vehicles are moving without any traffic jam. However, the Static-to-Static (S2S) communication model will not be evaluated since it does not reflect the IVC mobility. Thus, only the two communication models: S2D and D2D models, are simulated and evaluated. The parameter of evaluating those two communication models is shown in Table 6.3.

Table 6.3: Parameters of Inter-vehicle Communication Models

Parameter	Value
IEEE 802.11p Transmission Range	up to 1000 m
Number of Vehicles	20 - 100
Simulation Area	1000 m x 500 m
Obstruction Height	10 m
Static Mode Vehicle Velocity	0 km/h
Dynamic Mode Vehicle Velocity	40 - 70 km/h
Simulation Time	200 s
Number of Driving Lanes	2
Packet Size	1024 Byte

The first set of results in this simulation is shown in Figure 6.10 to 6.11 which indicates the network performance of the S2D and D2D communication models in the cross and parallel overpass scenarios. The ratio of the successful connection in both S2D and D2D communication models are less than 100% due to the road topology and overpass constructions. Thus, the communicating vehicles located outside of the transmission range do not get the full coverage. The PDR in the S2D communication model has lower percentages compare to the PDR in the D2D communication model. The lower PDR in the S2D communication model is caused by static vehicles that mainly in the status where the vehicles cannot search for a new path. Another reason is that he static vehicle is mostly located under the overpass construction. This occurs particularly in the cross road scenario. Thus, connections amongst vehicles are disrupted by the overpass construction. However, in overall scenarios and communication models: the parallel and cross road scenario, as well as the S2D and D2D communication models, are clearly indicate that the forwarding scheme implementing

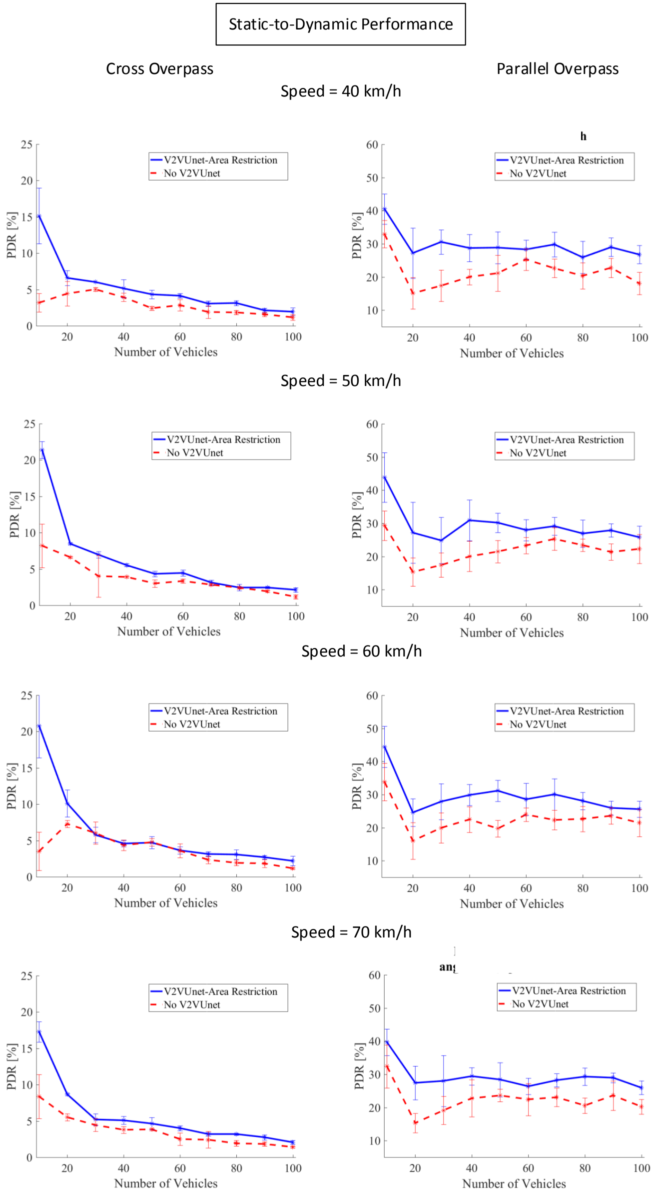

Figure 6.10: Static-to-Dynamic Communication Model Performance

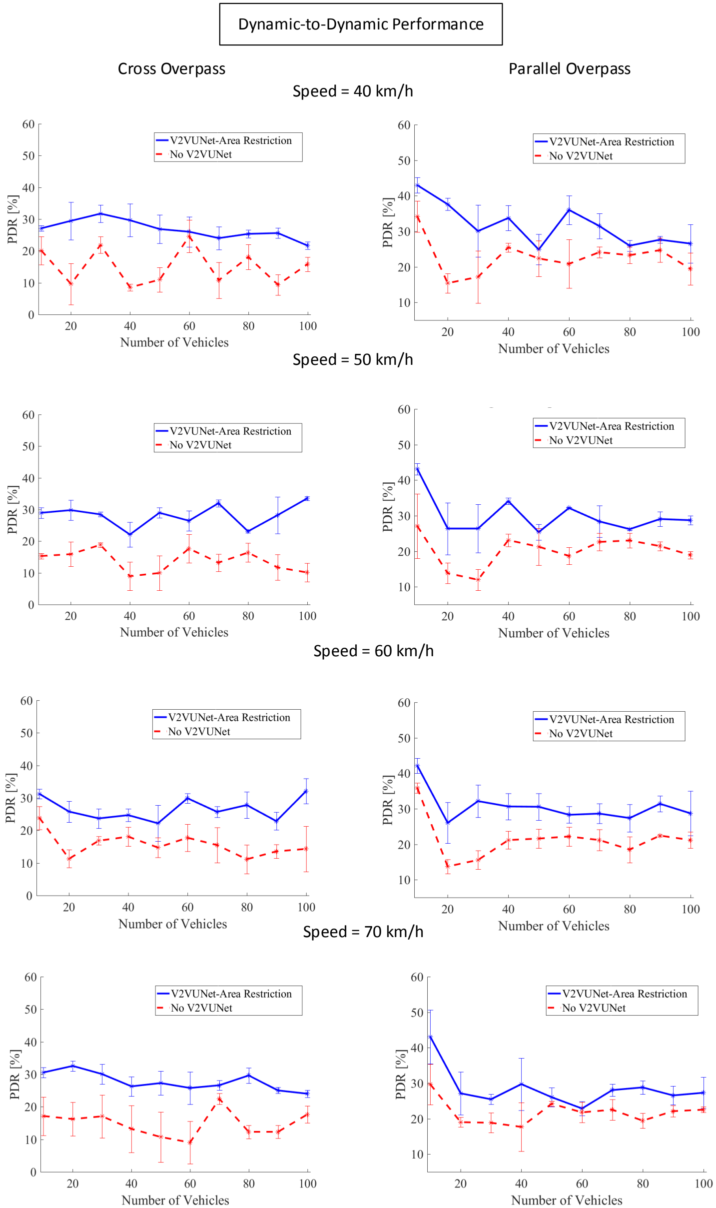

Figure 6.11: Dynamic-to-Dynamic Communication Performance

the V2VUNet approach has 10% better performance compare to the forwarding scheme without the V2VUNet.

The second set of results is shown in Figure 6.12 and 6.13. Those results indicate the E2E delays of each communication model. In the overall results, the higher E2E delays in the area restriction forwarding scheme are caused by the broken current path due to the high mobility. In the cross and parallel scenarios, both E2E delays indicate the significant value. In the cross scenario, the E2E delays reach until 300 ms. This delay occurs due to the overpass construction where the vehicle requires more times to find the new path. While in the parallel scenario, the E2E delays are less than 150 ms. Although the E2E delays of the area restriction forwarding scheme are higher that the E2E delays of the traditional forwarding scheme, however, the overall E2E delays are still acceptable in ensuring the reliable IVC.

6.3 V2VUNet-Path Prediction

The second approach of the V2VUNet: path prediction, is evaluated under the parameter and simulation environment as shown in Table 6.4, which is similar to the parameter of the area restriction forwarding scheme.

Table 6.4: Parameters of Path Prediction Evaluation

Parameter	Value
IEEE 802.11p Transmission Range	up to 1000 m
Number of Vehicles	20 – 100
Simulation Area	1000 m x 500 m
Obstruction Height	10 m
Average Vehicle Velocity	40 – 70 km/h
Simulation Time	200 s
Number of Driving Lanes	2
Packet Size	1024 Byte

The path prediction forwarding scheme is not evaluated in the parallel overpass scenario, since it is assumed that in the parallel overpass scenario, the direction of participating vehicles are uniform. The path prediction forwarding scheme will have a significant impact if the participating vehi-

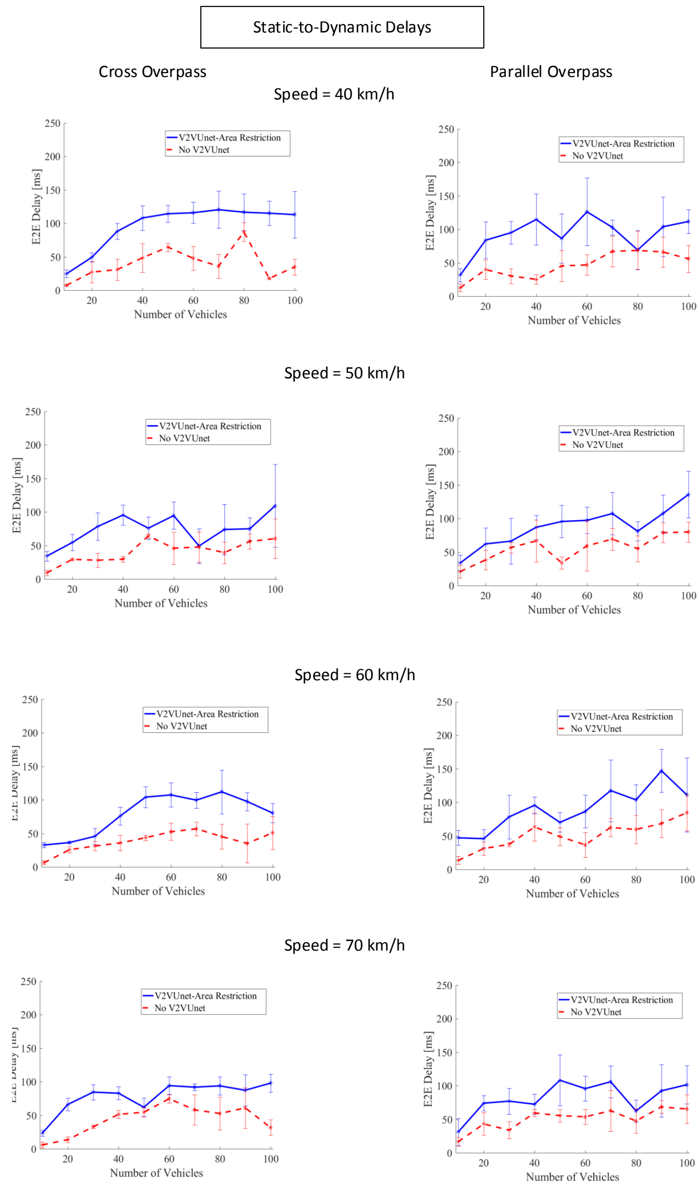

Figure 6.12: Delay in Static-to-Dynamic Communication Model

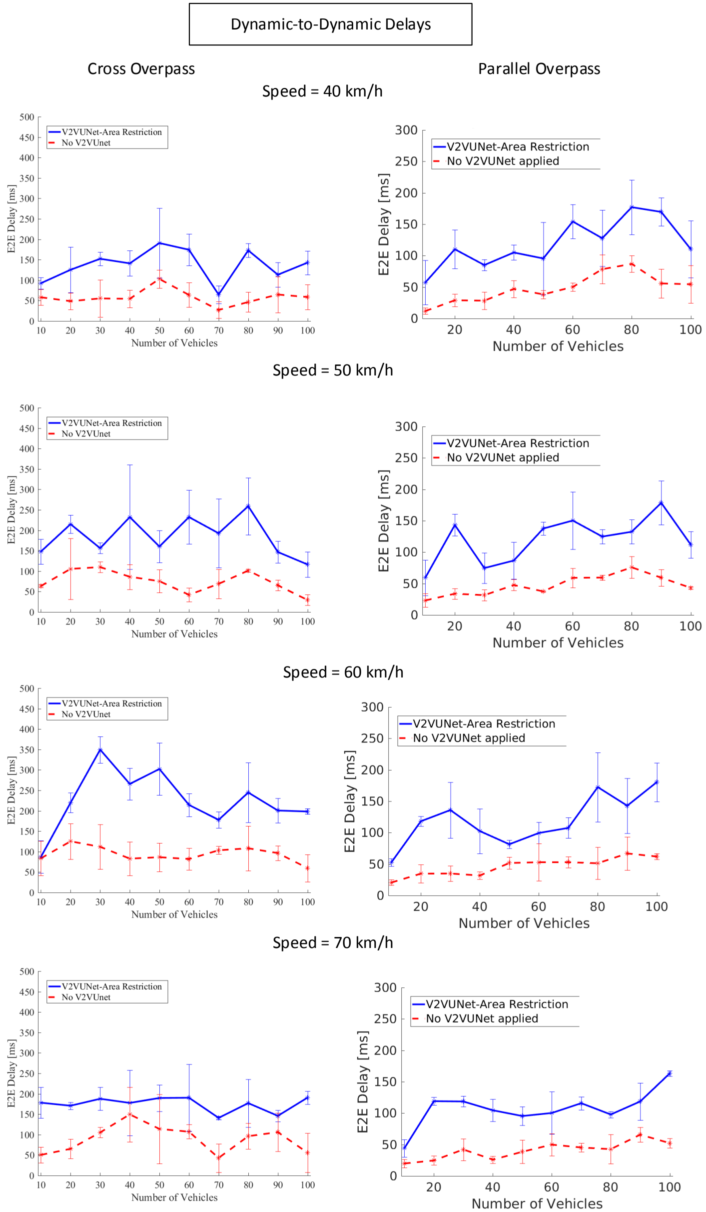

Figure 6.13: Delay in Dynamic-to-Dynamic Communication Model

cles have at least four directions as the vehicles run at the intersection road topology.

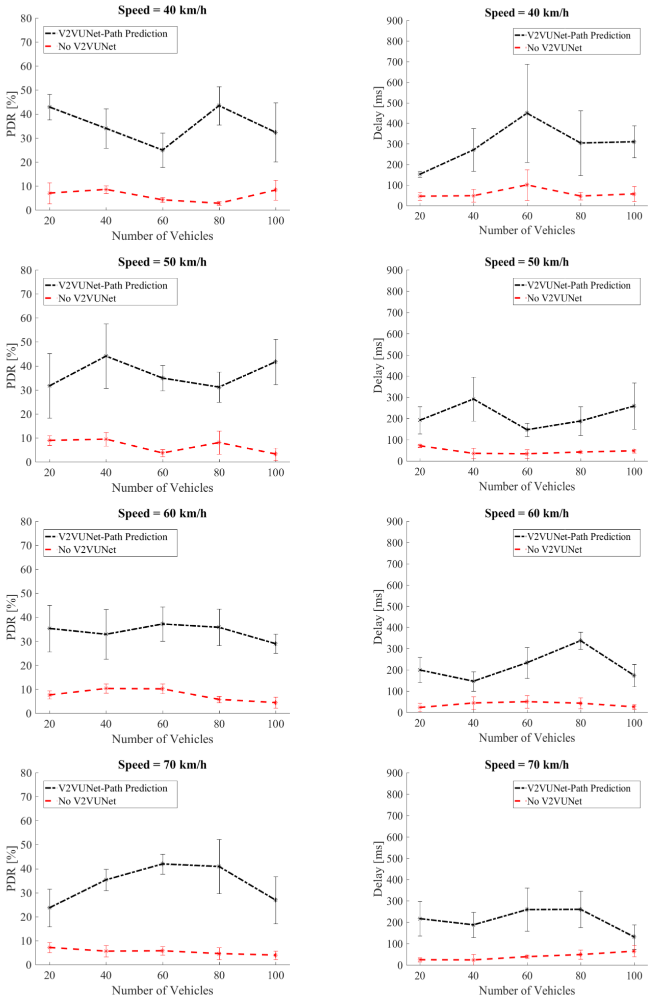

Figure 6.14: V2VUNet-Path Prediction Scenario

The set of results is shown in Figure 6.14. It reflects the sparse and dense networks, which is indicated by 20 to 100 participating vehicles, respectively. The results indicate that the PDR of the V2VUNet-path prediction forwarding scheme shows the better result compared to the traditional position-based forwarding scheme. The path prediction forwarding scheme improves the PDR up to 20%. From all PDR results, the path prediction forwarding scheme works best in at speed 50 - 70 km/h. The reason is that the algorithm in the path prediction forwarding scheme can estimate the high mobility of participating vehicles. Thus, by taking into account the vehicles' velocity, the prediction algorithm can calculate the life time connection between two communicating vehicles. The E2E delays which are shown in the results, however, have to be handled as a trade-off. This path prediction forwarding scheme has larger E2E delays at the speed 30 km/h. These delays indicate that the path prediction works properly at higher speeds.

6.4 V2VUNet Evaluation

This V2VUNet simulation combines all approaches: the area restriction, path prediction, and traditional position-based forwarding schemes. This simulation is conducted to compare the results of those three forwarding approaches.

6.4.1 Packet Size Evaluation

The evaluation of various size of packets: from 1 K to 10 KB, is conducted to investigate the bigger data packets transmission. The bigger data packets are applied in this simulation to reflect the non-safely applications, which usually have the data size bigger than 1 Kb. This packet size evaluation is conducted under the parameter and environments as shown in Table 6.5

Figure 6.15, shows the result of shows the PDR of three forwarding schemes when different packet sizes are applied. This evaluation simulates 40 vehicles that move with an average speed of 40 km/h. The V2VUNet-area restriction approach which is illustrated in the solid blue line, shows 20% better PDR compared to the traditional position-based forwarding scheme which denoted as "No V2VUNet". The V2VUNet-area restriction also shows 10% better compared to the V2VUNet-path prediction scheme,

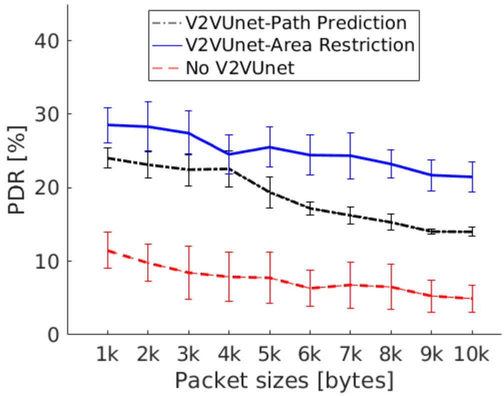

Figure 6.15: PDR in Various Packet Sizes

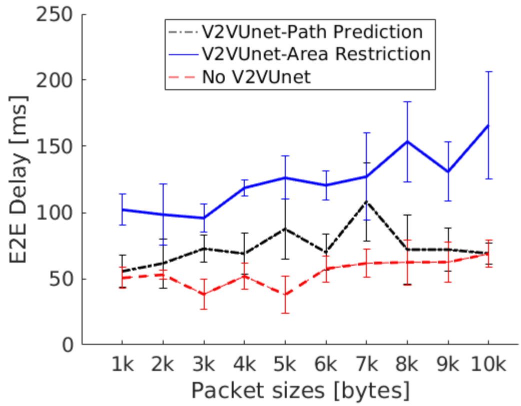

Figure 6.16: E2E Delay in Various Packet Sizes

Table 6.5: Parameters of Packet Size Evaluation

Parameter	Value
IEEE 802.11p Transmission Range	up to 1000 m
IEEE 802.11o Communication Range	up to 300 m
Number of Vehicles	10
Simulation Area	1000 m x 500 m
Obstruction Height	10 m
Average Vehicle Velocity	60 km/h
Simulation Time	500 s
Road Topology	Cross Overpass
Number of Driving Lanes	2
Packet Size	1 Kb to 10 Kb
Data rate	6 Mbps Constant Bit Rate

which is illustrated in the dashed-dot black lines. The showed PDR in overall algorithms decreases as the packet size increases, which indicates that the bigger packet size leads to low quality of transmission. The reason is that the bigger packet size needs longer period of transmission time. The required transmission time is influenced by the connection life time, especially at high speeds where the connection life time is very short (cf. 6.5). However, the V2VUNet approaches: the area restriction and path prediction forwarding schemes indicate that HRA and VRA weight values have significant impacts in packet transmissions. In addition, the area restriction shows better PDR than the PDR in the path prediction forwarding scheme. The main reason is that the area restriction forwarding scheme localize the participating vehicles within the forwarding area without considering the direction of the participating vehicles. On that forwarding area, the area restriction forwarding scheme maintains the intermediate vehicle without considering its direction. As far as the intermediate vehicle is still in a sender's transmission coverage, the sender keeps forwarding the packet. On the contrary, the path prediction forwarding scheme will disconnect the communication and find another substituted intermediate vehicle that has the most similar direction to the final destination, as has been described in the Subsection 4.5.2.

Further evaluations with different scenarios: the cross and parallel overpass road topology, and various numbers of vehicles with different speeds also reflect the same behavior as presented in Figure 6.17.

The second result shows the E2E delay of all algorithms which is illustrated in Figure 6.16).

The results show the E2E delay when different packet sizes are applied. The E2E delay increases as the packet size increases. This is because more time are required to transmit packet with bigger sizes. The highest E2E delay of 200 ms is indicated by the area restriction scheme because the area restriction scheme requires more time to substitute the current intermediate vehicle, which intents to move outside of the forwarding area, with the future intermediate vehicle, which fulfills the requirement. In overall E2E delay results, the traditional forwarding scheme provides lowest delay compared to other two algorithms.

This is because the traditional forwarding scheme does not need an additional mechanism to perform packet forwarding. The further E2E delay evaluations with different scenarios: the cross and parallel overpass road topology, and various numbers of vehicles with different speeds as presented in Figure 6.18 also reflect the same behavior. In overall results, the E2E delays have to be handled as the trade-off in order to obtain the better PDR by applying the V2VUNet.

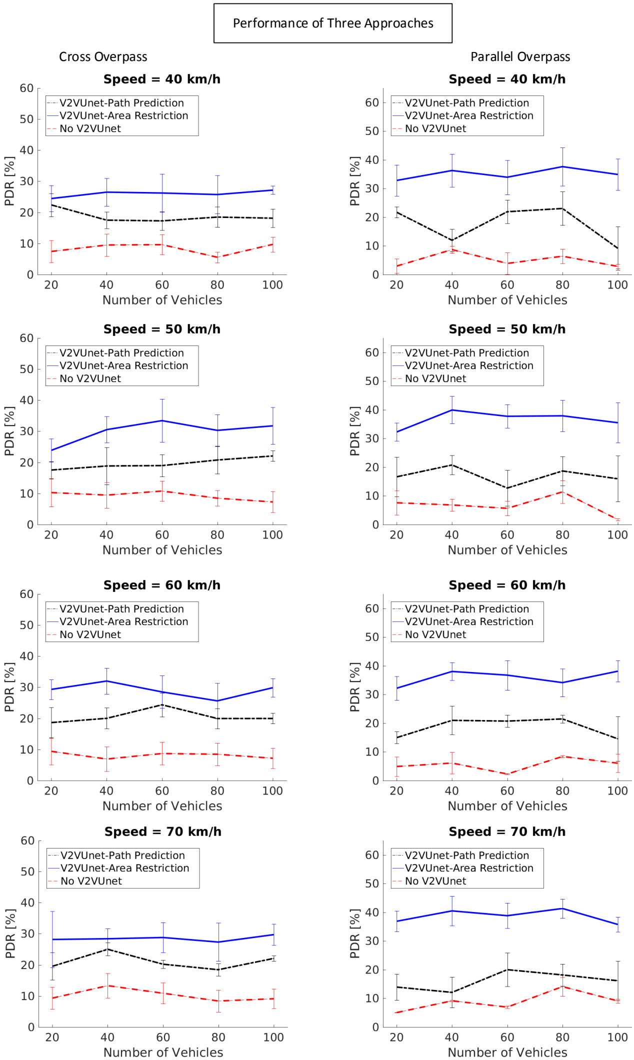

Figure 6.17: Packet Delivery Ratios for Varying Numbers of Vehicles and Vehicle Speeds Cross

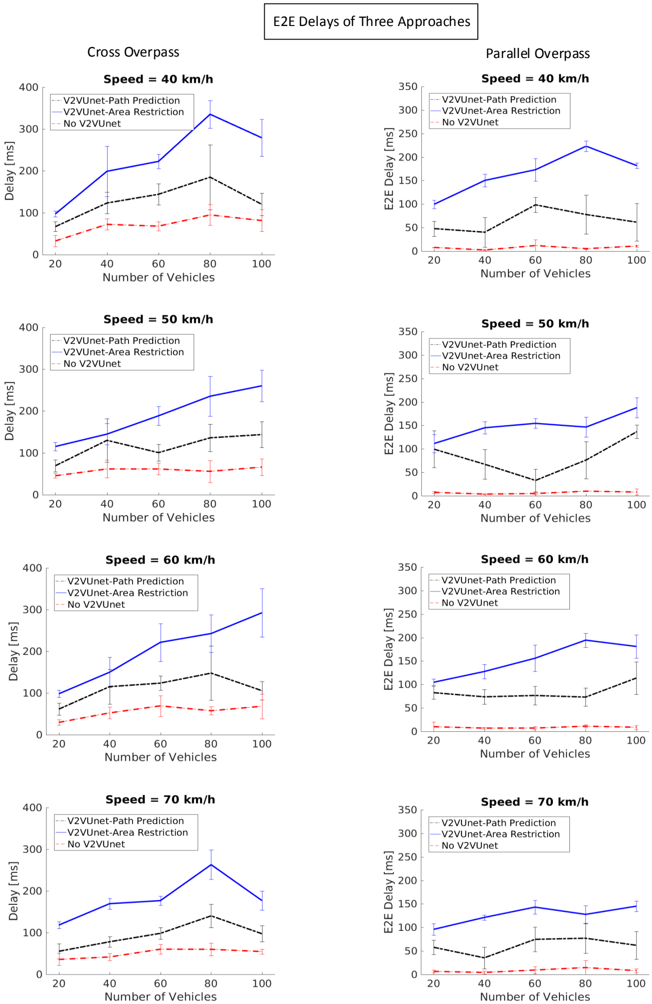

Figure 6.18: Delay for Varying Numbers of Vehicles and Vehicle Speeds

6.4.2 Complex Road Study

This simulation defines the improvement of two V2VUNet approaches: the area restriction and path prediction forwarding schemes. As described in Subsection 4.5.3, the enhanced V2VUNet combine those two approaches. To validate this enhanced V2VUNet, the scenario for this simulation applies the complex road topology as shown in Table 6.6. The Semanggi bridge as presented in Subsection 5.6.1, reflects the complex road topology. This complex road topology applies several significant factors: various vehicle's movements and directions, types of communication models, and four road layers with different heights. Figure 6.19 and Figure 6.20 show the network performance of V2VUNet implemented in a complex road scenario.

Table 6.6: Parameters of Complex Road Study

Parameter	Value
IEEE 802.11p Transmission Range	up to 1000 m
IEEE 802.110 Communication Range	up to 300 m
Number of Vehicles	20 - 100
Simulation Area	500 m x 500 m
Obstruction Height	5 - 20 m
Average Vehicle Velocity	600 km/h
Simulation Time	500 s
Road Topology	Cross Overpass, Parallel Overpass Clover-shaped, Circle-shaped
Number of Driving Lanes	2
Packet Size	1 Kb
Data rate	6 Mbps Constant Bit Rate

The first set of results in Figure 6.19 shows the network performance of enhanced V2VUNet compare to traditional position-based forwarding scheme. The dotted green lines represent the enhanced V2VUNet and the the dashed red lines represent the traditional position-based forwarding scheme which is denoted as "No V2VUNet". In overall PDR results, the performance of enhanced V2VUNet is 20% better than the traditional position-based forwarding scheme. As the speed increases, the network performance of the enhanced V2VUNet is slightly decreased. Moreover,

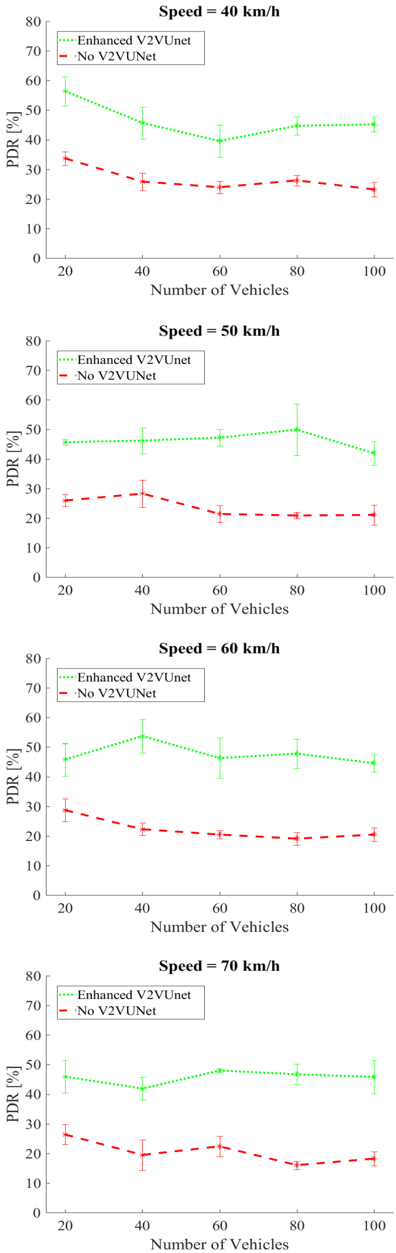

Figure 6.19: Enhanced V2VUNet in a Complex Road Topology

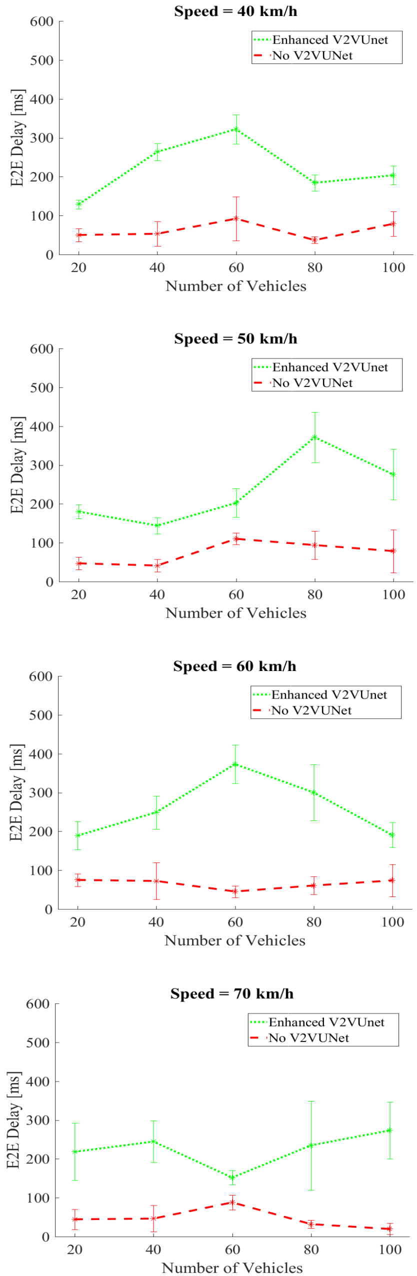

Figure 6.20: Enhanced V2VUNet Delays in a Complex Road Topology

the number of vehicles influence the PDR results, since the number of source and destination vehicles pairs increase. However, the overall results show 50% of PDR. This improvement is considered as the significantly positive to guarantee a reliable IVC.

The second set of results in Figure 6.20 shows the E2E delays which are measured from the time a source vehicle starts to transmit the packet until the packet reach the destination vehicle. This E2E delay in the enhanced V2VUNet is caused by the area restriction algorithm that significantly requires the additional period of time to locate the new intermediate vehicle. Moreover, the fluctuating E2E delays are caused by the initial random placement of vehicles that can cause the connection or disconnection between pairs of vehicles at the beginning of simulation specifically for the complex road topology. Thus, those delays of two approaches show dissimilar pattern. However, these E2E delays are still acceptable to provide the non-safety application in the IVC.

7

Conclusions and Future Work

This thesis investigated and evaluated the feasibility of inter-vehicle communications. The investigation of inter-vehicle communication focused onto a 3-dimensional environment, and the evaluation was done under various traffic road conditions and environments. The reliable inter-vehicle communication in the 3-dimensional environment had to address combined challenges of a complex road topology, high mobility, and number of bytes. The overall results show that there were several significant impacts of integrating these challenges as additional parameters exist to improve the packet forwarding scheme.

7.1 Conclusions

V2VUNet has addressed the 3-dimensional environment and determined the 3-dimensional awareness. V2VUNet has introduced HRA and VRA as weight values and improved the position-based forwarding scheme. The 3-dimensional awareness has detected the important point regarding to the

3-dimensional area, such as the inevitable obstructions, which might not be found in other 3-dimensional cases.

The road topology level leads to the strategy to design the proper packet forwarding scheme. This thesis has proposed and evaluated the forwarding scheme called V2VUNet. The V2VUNet is designed to improve the traditional position-based forwarding scheme with two approaches: the area restriction and the path prediction forwarding schemes, which maintain a better inter-vehicle communication. The first approach *i.e.,* area restriction forwarding scheme, is designed to restrict the area for unwanted intermediate vehicles, The second approach *i.e., predictive forwarding scheme,* is designed by predicting the direction of intermediate vehicles. Those two approaches in the V2VUNet use the Horizontal Relative Angle (HRA) and the Vertical Relative Angle (VRA) as the important weight values.

The evaluation concludes that the factors of the 3-dimensional road topology such as different heights of road, cross- or parallel overpass construction, and static or dynamic communication models have significant impacts to inter vehicle communication.

Regarding to the better improvement of V2VUNet in terms of PDR, this approach is expected to be more practical since the further mobile communication developments such as implementing the non-safety application in a public transportation, will be the future IVC in Indonesia. However, the further calculation of delay can be measured, thus, raising a solution such as implementing carry and forward algorithm or installing Road Side Units (RSUs).

7.2 Review of Contributions

Challenges as indicated in Section 2.5 were addressed and determined into V2VUNet contributions as follow:

- Obstacles as the first challenge, the overpass construction which was located above a straight road, is determined to be the inevitable physical obstacle. Thus, V2VUNet addressed the obstacle issue by introducing the obstacle awareness propagation model.

- Distance as the second challenge, the distance was analyzed in two cases. V2VUNet addressed the oversimplification of a 3-dimensional case onto a 2-dimensional case. Thus, V2VUNet introduced the area dimensional detection by detecting the position coordinates and defining the distance between two respective vehicles as HRA and VRA.

- Velocity as the third challenge was defined as speed and direction of a vehicle. The simulation in this thesis was conducted in the large city environment where a vehicle runs in high speed (more than 70 km/h) is not suitable especially in Jakarta, Indonesia. Thus, V2VUNet does not indicate speeds as the significant challenge. However, the orientation of vehicles were indicated in the relative direction which becomes part of HRA and VRA. Thus, V2VUNet addressed the direction as the additional weight value in its forwarding scheme.

- Duration of connectivity which becomes the fourth challenge was addressed by V2VUNet. V2VUNet maintains the longer duration of connection among the communicating vehicles by selecting the intermediate vehicle that has the same direction with the sender vehicle, as indicated in HRA and VRA weight value.

7.3 Future Work and Outlook

Since the V2VUNet is an open position-based forwarding scheme, this means that the scheme has the possibility to be improved in various ways. The approach can be varied based on different scenarios, technologies, and other parameters, such as data rates and velocities. Thus, the V2VUNet forwarding scheme can be applied to any position-based forwarding schemes, especially, by applying the online map of a road traffic and a city environment, which will provide real time information, such as traffic densities and vehicles' velocity. As a consequence, these online map will be an improvement for operating IVC in real time.

The delay as the trade off, still needs to be reduced in order to meet a reasonable user's Quality-of-Experience (QoE) in implementing IVC, particularly for non-safety applications.

The concept and technology of 5-generation (5G) communication in the future, brings a new point-of-view in IVC. As 5G communication offers determine promising communications, they could be integrated into IVC to improve the overall IVC performance in terms of communication range, heterogeneous communication models, and cloud-based communication. Other advantages in integrating IVC and 5G are the deployment of a better QoE for passengers in public transportation and the supportive communication in small cells to accommodate even more traffic. While IVC in 5G needs to address four challenges currently influencing today's architectures: air medium transmission, congestion due to heavy data interchanges, mobility management, and security, the costs required to install 5G communications infrastructure are large and go well beyond those schemes and communication alternatives evaluated within this thesis. Additionally, this integration will have to ensure a smooth cooperation and implementation between non-cellular-based communication and cellular-based communication.

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Curriculum Vitae

Lisa Kristiana was born on October 25, 1975, in Semarang, Indonesia. In 2001, she obtained a Bachelor of Science in Electrical Engineering from the Soegijapranata Catholic University (Unika), Semarang, Indonesia.

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Her main research interests are Mobile Ad-hoc Network (MANET) and Vehicular Ad-hoc Network (VANET). Her doctoral thesis was supervised by Prof. Dr. Burkhard Stiller (University of Zurich, Switzerland) and Prof. Dr. Frank Kargl (University of Ulm, Germany).

Other Publication

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- L. Kristiana, C. Schmitt, B. Stiller, "Survey of Angle-based Forwarding Methods in VANET Communications", *Wireless Days, WD*, Toulouse, France, IEEE, March 2016, pp. 1-3.
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